

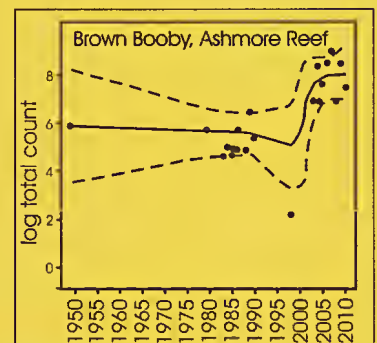


Journal of the Royal Society of Western Australia



Symposium on Kimberley Marine and Coastal Science

Proceedings of a joint RSWA/WAMSI Symposium held in May 2011,
convened by S Blake and V Semeniuk



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The Journal of the Royal Society of Western Australia was first published in 1915. Its circulation exceeds 650 copies. Nearly 100 of these are distributed to institutions or societies elsewhere in Australia. A further 300 copies circulate to more than 40 countries. The Society also has over 350 personal members, most of whom are scientists working in Western Australia (see website <http://www.rswa.org.au>). The Journal is indexed and abstracted internationally.

Cover: Sequence of images from the Kimberley coastal region. Top left hand to bottom right: Prince Regent River area with Mt Trafalgar (image courtesy of Yann Arthus-Bertrand); large meandering tidal creek in a mangrove-inhabited narrow shaped embayment (photograph Margaret Brocx); and the Horizontal Falls in the Buccaneer Archipelago (photograph Steve Blake). Bottom left corner, the Freshwater Sawfish, *Pristis microdon* (image courtesy of Dean Thorburn). Top right is a graph from Clarke *et al.* (this volume) showing log transformed total counts of a ground-nesting large-bodied seabird, the Brown Booby, breeding at the Ashmore Reef.

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PREFACE



In 2009, following the successful Symposium on the Leeuwin Current off Western Australia and publication of the Symposium Proceedings in a Special Issue of the Journal of the Royal Society of Western Australia, the Western Australian Marine Science Institution (WAMSI) approached the Royal Society of Western Australia (RSWA) to jointly convene a similar style symposium on the coastal and marine science of the north west of WA, with particular focus on the Kimberley region. It was subsequently decided there was likely enough scope to divide the north-western coast [defined as the region from Exmouth to the Northern Territory border] ultimately into three Symposia, that is, the Kimberley, the Canning Coast, and the Pilbara Coast. This Kimberley Symposium represents the first of the anticipated series.

The Kimberley Symposium has been assembled under the directorship of a steering committee composed of WAMSI, a RSWA Council sub-committee, WA's Department of Environment & Conservation, the CSIRO, Australian Institute of Marine Science (AIMS), and the Kimberley Land Council. The objective of the Symposium is to bring together the latest research, and reviews of work carried out to date on the Kimberley marine and coastal environment into a single symposium and publish a seminal RSWA Special Issue Volume to provide Western Australian, national and global scientists with the available information in the public domain. The Kimberley coastal and marine region is a globally unique environment and thought to be in the last four per cent of undisturbed tropical marine ecosystems left on Earth.

In view of the Aboriginal custodianship and traditional knowledge of the Kimberley region, representatives of Traditional Owners of the Kimberley Saltwater Country (the Kimberley rocky coast) and the Dampier Peninsula were consulted and involved in the planning and presentations at the Symposium and the Special Issue. In recognition and respect of the Aboriginal custodianship, the Symposium commences with an opening by Donny Woolagoodja, an Elder from Saltwater Country, and ends with Bibido McCarthy (a regional Bardi Jawi ranger) describing the monitoring and management of the coastal and marine environment under the auspices of the Aboriginal Traditional Owners.

This Symposium and Special Issue Volume brings to fruition two years of planning and, later, manuscript submission, peer-review processing and subsequent paper publication. The Committee set up to manage the Symposium decided early on to endeavour to have the Special Issue published and available for distribution at the one-day Symposium, and this objective was met. Such an ambitious endeavour is not normally attempted and so congratulations are in order to the RSWA editing and publishing team.

It would be true to say that the Kimberley region has not historically had the same focus of research funding and coordination as other marine regions in Australia, highlighting the importance of summarising what we do indeed currently know. This landmark Special Issue therefore covers many aspects of Kimberley coastal and marine science, from the wholly abiotic to the complex ecological, and presents new and summary aspects of the science of the Kimberley coastal and marine environment into a single compendium, a first for the region.

The Symposium presentations and the published papers have been broadly organised into a sequence reflecting abiotic *versus* biological aspects of the region, with biological components arranged from the lower to the higher trophic levels. The papers range from the global significance of the geological features of the Kimberley, to sedimentation, coral reefs, coastal vegetation and mangroves, plankton, invertebrate fauna, turtles, whales, fish, crocodiles, sharks, turtles and fisheries, covering nearly every aspect of the Kimberley environment, with reference lists that will enable readers to further research these fascinating natural history facets of the region.

We thank and congratulate the Editors, the authors, and all those involved with the organisation of the Symposium, on furthering our scientific knowledge of this globally important and highly remote area of Western Australia. We hope this Special Issue on the science of the marine and coastal region of the Kimberley will form the foundation for further public research and thus to sound management of the environment for future generations. This can only be achieved through the integration of Western Science, traditional Aboriginal knowledge, and accompanying best-practice policies and supporting management.

The Symposium Organising Committee comprised: Steve Blake (Convener; WAMSI CEO), Linda McGowan (WAMSI), Vic Semeniuk (Convener; Vice-President, and Publicity Officer, RSWA); Margaret Brocx (Sub-editor, RSWA), Alan Pearce (RSWA), Stephen van Leeuwen (Department of Environment & Conservation), Tom Hatton (CSIRO) and Andrew Heyward (AIMS), and are all to be congratulated on their efforts to organise the Symposium and to bring together this exciting range of papers on the Coastal and Marine Environment of the Kimberley Region.

Thanks also go to all the Symposium sponsors whose names are listed on the cover of this volume, but especially to the CSIRO Wealth from Ocean Flagship, the Australian Institute of Marine Science, Woodside Energy Limited, and VCSRG P/L as the Major Sponsors of the Symposium. RSWA and WAMSI also wish to acknowledge the Western Australian Museum for their support in hosting this event.

Steve Blake and Vic Semeniuk
Symposium Conveners

4 May 2011, Perth, WA.

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The Kimberley Coast – Saltwater Country – a Traditional Owner's perspective

Donny Woolagoodja

Senior Traditional Owner
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The Traditional Owners of the coast of the Kimberley region, known as Saltwater Country, comprised today of the Bardi Jawi, Malaya, Wanjina Wunggurr Dambimangari, Wanjina Wunggurr Uguu, and Balangarra peoples, have a long history of association with the landscape, seascape, flora and fauna of this region. Their history stretches back at least 30,000 years (O'Connor 1999), during the last Ice Age, and before the time of the marine flooding of the Kimberley region. Since the time of the marine flooding, perhaps some 7000 years ago, when the present Kimberley coast was formed, they have had a close association with the coastal landscape, the islands, the seascape, the coastal flora and fauna, and the marine life. Archaeological research shows the long term association of Saltwater people and the coastal environment (Veitch 1999) since the marine flooding.

In this setting of Saltwater Country, the Wanjina Wunggurr Saltwater people share a commonality of environment, law, and culture, and like other Australian Aboriginal people their belief system is connected with the Wunggurr rainbow serpent and other creation beings. Commonly termed "The Dreaming", it is considered to be the longest continuing belief system in the world, and the Traditional Owners of Saltwater Country strongly identify with "Wanjina", anthropomorphic creation beings, in their law and culture.

Aboriginal Saltwater people live their lives in coastal and marine environments, as distinct from Freshwater people who live on rivers and inland country. They see the coast and seascape as part of their traditional lives – and they are the custodians or caretakers of this environment. Their involvement and attachment to the land is multiple: it is their home, their physical place, their own personal spiritual place, an area that provides food and water, shelter, and a place that has tribal spiritual connotations and history. For the Traditional Owners along the Kimberley coast there are majestic sea cliffs, mineral-stained sea cliffs, islands, mud flats, tide movements, areas of freshwater seepage, rainforests and vine thickets, reefs, mangroves and, in the realm of coastal life, fish, mud crabs, turtles, dugongs, stingrays,

sea birds, amongst many others. They see the country as unspoiled, and as they look after what they call "our country", they feel that the country looks after them – it is a two-way spiritual connection.

Their association with the land is that they are part of the land. They carry a traditional knowledge and familiarity about the land, coast and seascape, passed down through the generations, and gained from personal experiences, that is different to that of the Western Scientist, and that has long served them as a People to be able to survive in their environment. Their knowledge of the migration and arrival and breeding seasons of various coastal and marine animals, for instance, though different to that of hard-data science and may be anecdotal to Western Scientist but is based on long-term observations of patterns, and enables them to be at the right place and right time to hunt or harvest specific species. Their knowledge of water occurrence and movement enables them to be at the right time and right place to harvest life-sustaining water. It may not be 20th Century Scientific technique but it is information about patterns of land, water and life that enabled and enables them to survive in Saltwater Country.

The Traditional Owners actively live/lived on the coastal lands and islands, harvesting shell fish, oysters, and shipworm, hunting turtles and dugongs, and catching fish and stingrays, obtaining freshwater, and sheltering in caves and rock overhangs. In from the coast, they hunted kangaroo, snakes, lizards, and other animals, harvested plant life in terms of fruit and roots, and other "bush tucker". Originally they harvested and hunted using traditional means, but in recent times have employed the use of technology. They also utilized certain plants for boat-making ("kalwa"), charcoal-making (for ochres), and stunning fishing.

On a final note, I hope have transmitted here that the Traditional Owners of Saltwater Country have a respect for the land, a belief that the land looks after its inhabitants if they look after it, and that the Traditional Owners have a core natural history knowledge of the landscape, water and ecology of the coastal Kimberley that has served them well for thousands of years.

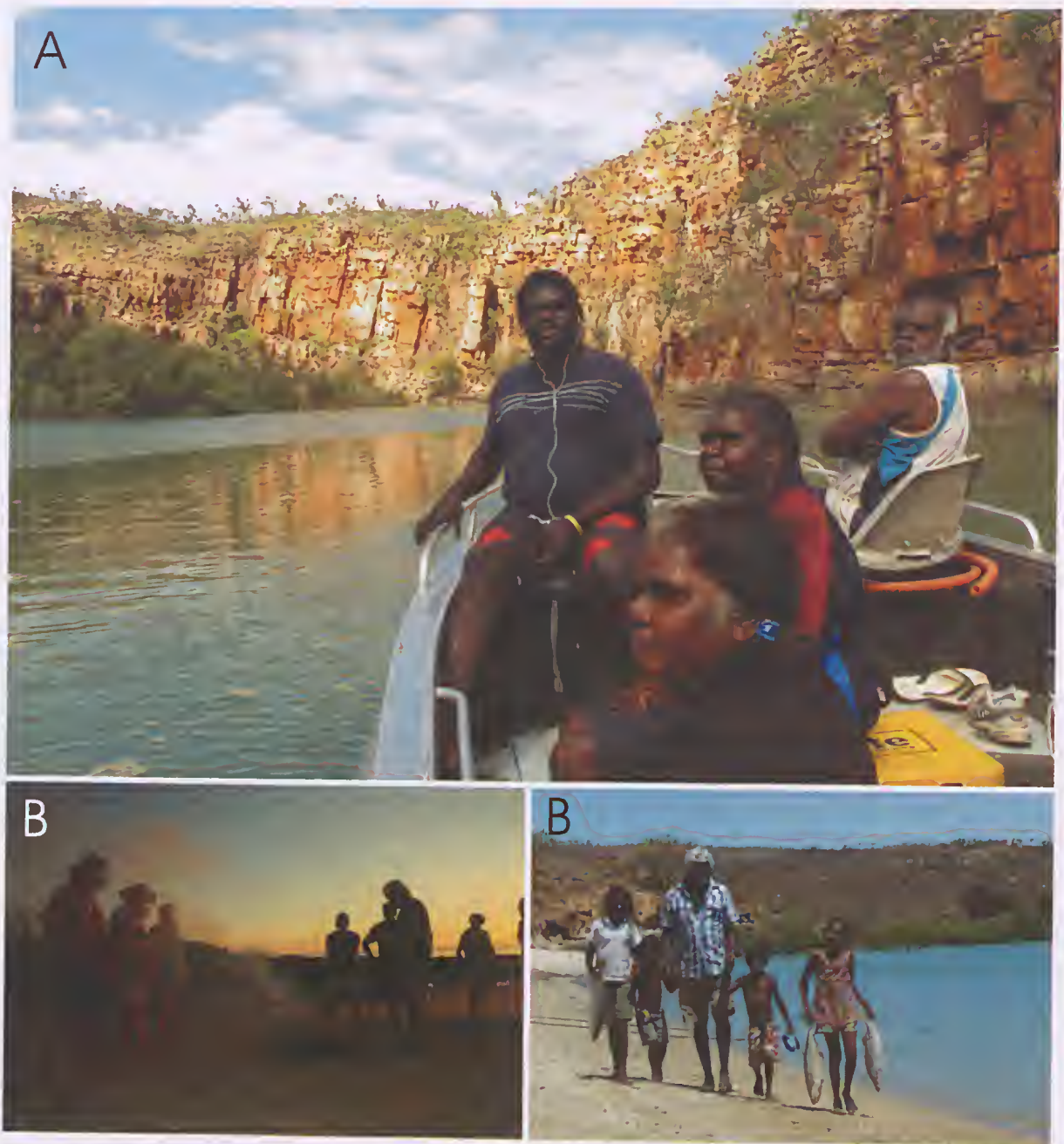


Figure 1. A. A spiritual place where stories are told to pass on information to others and to the next generation. In this place, there is "river" rock", which tells a story of the flood that transported rock to the (now) offshore islands. It tells a story about the river floods that took place before the marine flooding of the landscape that created the present coast. It is also a spiritual place because of "Wanjina", the Father of the Country. "Wanjina" tells the Traditional Owners where to live, how to live, what to eat, where is the freshwater, what are the rules (the Law). B. When visitors or strangers arrive to a place to share a story or knowledge about the coastal lands, or to be introduced to the values and beliefs of the Saltwater Country Traditional Owners, there is first need for a cleansing to prepare them to come to Saltwater Country. In this photograph, some visitors on the left are being traditionally cleansed by smoke from the leaves of a special plant burnt for this purpose by the Traditional Owners on the right. C. Yaloon, a special place, where training and teaching takes place. Here, a catch of barramundi is being ferried home for cooking.

The global geoheritage significance of the Kimberley Coast, Western Australia

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Abstract

The Kimberley Coast in north-western Australia is of global geoheritage significance. It is a large-scale ria coast, with a well developed intricate indented rocky shoreline, with local nearshore islands (archipelago), and a distinct suite of coastal sediments. In addition to its intrinsic geoheritage values, its unique geological and geomorphological features are found in an unspoiled wilderness setting in which *the ensemble of natural processes are still operating*. The Kimberley Coast is cut into Precambrian rocks: the sandstones and basalts of the Kimberley Basin and, in the southern areas, into folded sedimentary rocks and metamorphic rocks of the King Leopold Orogen. The rocks of the region are well exposed along the shore to providing a global classroom by which to study the region's stratigraphy, structure, and lithology. The coastal forms in the Kimberley region have been determined by the structure and lithology of regional geology, interfaces between major geological units, by marine inundation of onshore landforms, and by the sizes, shapes and configuration of rivers, creeks, their tributaries, and other valley tracts in the region. The coast, however, is not just a continuous rocky shore composed of cliffs, and cliffs with benches, as it also has local sediment-filled gulfs and embayments, cliff shores fringed by mangroves, cliff shores with bouldery ribbons in the tidal zone, and stretches of beaches, and in the embayments, muddy tidal flats, spits, cheniers, tidal creeks cut into the tidal flats, and (embayment-head) alluvial fans. Locally, the coast is composed of algal reefs and coral reefs, beach rock, and various types of tempestites.

The Kimberley Coast presents several features of geoheritage significance: 1. with ~ 700 km of (simplified) coastal length, it presents the best and most extensive expression of ria morphology in Australia, and also one of the best developed globally; 2. the occurrence of the shore in a monsoonal subhumid/humid tropical macrotidal setting, with processes distinct to this setting; as a tropical-climate ria, in terms of size and morphology, it is globally unique; 3. the morphology of the shores, variable in form in response to the grain of the country (*viz.*, the Kimberley Basin *versus* the King Leopold Orogen) and lithology; 4. variation of rocky shores along its length in terms of mesoscale shore types; 5. the sedimentary packages that occur in the region; 6. mangrove-lined rocky shores and embayed shores, with the latter also related to freshwater seepage; and 7. biogenic and diagenetic coasts.

Keywords: Kimberley Coast, ria coast, tropical coast, macrotidal, Proterozoic rocks, geoheritage

Introduction

Globally, only a few coasts have been described and assessed as to their geoheritage significance and this paper provides an opportunity to describe the Kimberley Coast of Western Australia (Fig. 1) and address its geoheritage significance from an International and National perspective. While there have been studies and geoheritage assessments of some rocky coasts in Australia of National or of State-wide significance (*e.g.*, Hallett Cove in South Australia, The Twelve Apostles in Victoria, and Ulladulla cliffs and platform in New South Wales; Packham 1969; Parkin 1969; Dixel & Preiss 1995; White *et al.* 2003) and overseas (*e.g.*, Siccar Point in Scotland, The Seven Sisters of southern England, the Giant's Causeway in Ireland; Gallois 1965; Melville & Freshney 1982; Soper 1984; Bennett 1989; Sale *et al.* 1989;

Jagla & Rojo 2002; Brocx & Semeniuk 2007), ironically, the Kimberley Coast, the largest rocky coastline in Australia and one of the most distinctive ria coasts globally, before now, has not been formally described and assessed for its geoheritage value.

Interestingly, because it is an extensive and essentially a single coastal unit, the Kimberley Coast challenges many concepts in natural science and classification in the coastal zone. For instance, the essence of what is a "ria coast" in plan form and relief is tested here, and the extremes of coastal types that constitute "ria shores" are present in this one region. For instance, geometrically, because of the regional geology, the ria coast of the Kimberley region grades from classic narrow ravines and inundated riverine valleys (traditionally, the most accepted notion of a ria) to broader embayments (indented coasts) to marine-inundated ridge-and-basin topography (also termed ridge-and-valley topography; Fairbridge 1968a). Apart from geomorphic



Figure 1. Location map of the study area.

considerations, the Kimberley Coast, as a rocky shore, also uniquely exhibits along hundreds of kilometres of shore extensive outcrop of Precambrian rock that indicates relative tectonic stability since the Proterozoic, and a contact along sea cliffs between a Proterozoic sedimentary basin and a Proterozoic tectonic zone (now an orogen). Additionally, the coast resides in a tropical monsoonal and generally macrotidal environment, with a strong inter-annual influence of cyclones, factors not comparable to ria coasts developed elsewhere in the world, with the consequence that coastal forms and products developed here are unique to this region. Finally, the coast is geomorphically varied in its orientation so that different parts of the coast are subject differentially to the coastal processes of tides, wind, wind-waves, swell, and cyclones such that, even though the geology is relatively simple and generally uniform from a regional perspective, there is significant sedimentary heterogeneity.

This paper is an account of the Kimberley Coast in Western Australia, with a description of the coastal forms, the reasons underpinning the development of the various coastal types, and the geoheritage significance of the coast at International and National level. However, in order to put the Kimberley Coast, as a ria coast, into geoheritage perspective, several matters are first discussed: the concept of ria coast, the theory underpinning geoheritage, the scope and scale of features of geoheritage significance, the levels of significance afforded to geoheritage sites, coastal classification in relation to geoheritage, and methods of inventory-based site-identification and assessment.

There are several ways of viewing the length of the Kimberley Coast. Using a simplified over-arching measure, it has a length of ~700 km. This is the measure used to compare other ria coasts elsewhere in Australia and globally. A more detailed measure involves adding the interior lengths of embayments, inlets, and large bays. From this perspective, the Kimberley Coast has a length of ~4000 km.

This paper is based on a combined 50 years of study in the Kimberley region by the authors. The sites described in this paper have been examined by field work, involving boat-work, land-based vehicle access, aerial surveys by fixed wing aircraft, and helicopter. All surveys were accompanied by intensive documentary photography. Additional work was carried out by desktop aerial photographic studies. On-site studies involved description of coast as to form and lithology, sampling of sediments, and determination of Quaternary stratigraphy by augering and from cliff exposures. Samplings sites, and flight paths for fixed wing aircrafts and helicopters are shown in Figure 2.

What is a ria coast?

In the literature there has been debate about what constitutes a *ria* and a *ria coast* (Johnson 1919; Cotton 1956; Fairbridge 1968b; Castaing & Guilcher 1995; Evans & Prego 2003). The term “*ria*” originates from the Spanish *ria* (from *rio*, or “river”). The term derives from describing the large narrow inlets on the coasts of Galicia (Fig. 3), north-western Spain (such as the Ria de Arosa and the Ria de Muros y Noya), being former valleys that were submerged by relative sea level rise due to eustatism or by submergence. Richthofen (1886) first defined a *ria* as a marine-inundated valley cut parallel to a regional geological strike transverse to a coast. However, to date, the term *ria* has carried with it a number of implications and misapplications. For instance, while the term carries connotations of a river valley, there are *ria* systems, identified globally, which are not river valleys, but inundated ridge-and-basin landforms (e.g., south-west Ireland), where the geological (structural) grain is transverse to the coast (Richthofen’s original definition). *Fjords* (marine-flooded glacially cut valleys) are excluded from the river valley concept of *ria*, yet some fjords have alternated from being glacially carved to fluvially incised. Some authors, however, include fjords where the term *ria* has come to mean any marine-inundated valley. The use, misapplication, extension, and strict application of the term *ria*, were discussed by Cotton (1956), separating “*ria sensu stricto*” and “*ria sensu lato*”, with an argument centred on the rias of Galicia on the coast of Spain, which, though comprising the original etymology of *ria*, do not themselves meet the definition *sensu stricto*. More modern usage has modified the definition (see below) such that the term “*ria*” is now a synonym for any marine-inundated valley without any structural constraint. As marine-inundated river valleys, rias generally have a dendritic to trellis pattern, reflecting the nature of the drainage of the ancestral rivers (Fig. 3), and remain open to the sea (e.g., Chesapeake Bay, United States of America; and Port Jackson, New South Wales).

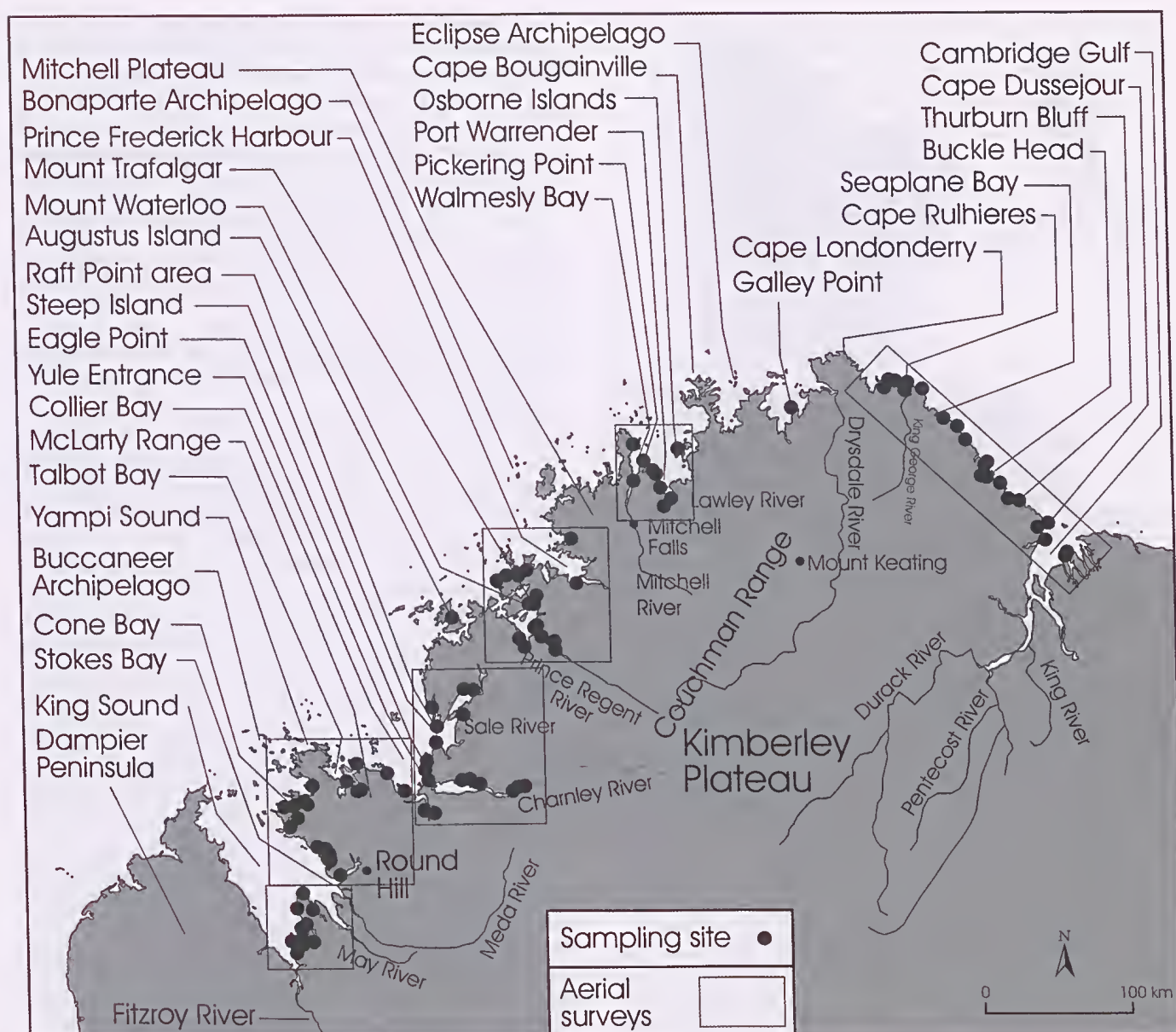


Figure 2. Sampling sites and place names mentioned in text.

Jackson (1997), drawing on a history of the use of the term, describes a ria as any long, narrow, sometimes wedge-shaped inlet or arm of the sea (but excluding a fjord) whose depth and width gradually and uniformly diminish inland, and which is produced by marine inundation due to submergence of the lower part of a narrow river valley or of an estuary. As such, it is shallower and shorter than a fjord. Jackson (1997) also notes that originally the term was restricted to inlets produced where the trend of rock structure is transverse to the coastline, but was later applied to any submerged land margin that is fluvially dissected transversely to the coastline. Less restrictively, a ria is defined as any broad or estuarine river mouth, *including* a fjord, but not necessarily an embayment, produced by partial submergence of an open valley. In this context, following Jackson (1997), a *ria coast*, building on the concept of a *single ria*, is one having several long parallel rias extending far inland and alternating with ridge-like promontories (e.g., the coasts of south-western Ireland or north-western Spain). Similarly, a *ria shoreline* comprises

numerous rias produced by marine inundation of a land margin subaerially dissected by numerous river valleys (Johnson 1919).

Bird (2005) also provides an overview of the concepts of *rias* and *ria coasts*, and describes a ria as a long, narrow, often branching inlet formed by marine submergence of the lower parts of a river valley that had previously been incised below present sea level. Bird (2005) notes that rias are the inundated mouths of *unglaciated* valleys, usually bordered by steep slopes rising to mountains, hills, or plateaux. Clearly, fjords are excluded from the definition. There is also implication that rias are developed in a range of geomorphic settings from deeply incised valleys (*i.e.*, bordered by steep slopes) to moderately incised valleys (*i.e.*, bordered by hills). Bird (2005) cites the long, straight valley-mouth gulfs on the south-west coast of Ireland (Fig. 3) as examples of rias – these follow a geological strike that runs transverse to the general coastline (a ria according to Richthofen 1886), and notes that where rivers have cut valleys across



Figure 3. Rias from Galicia (Spain), south-western Ireland, and Sydney (NSW). Bar scale 50 km

geological structures there may be tributaries that follow the geological strike, submerged to form a trellis pattern, as in Cork Harbour in southern Ireland. Another classic example of a ria coast following the definition of Richthofen (1886) occurs along the Dalmatian coast of the Adriatic Sea where rias are elongated marine straits along valleys that follow the geological strike, linked to the sea by transverse channels.

Ria coasts around the world vary in size, shape and geology and, moreover, vary with respect to the relief of the adjoining hinterland. However, to date, no author has delineated a size limit or a size range to a ria. The type sites of rias referred to by Richthofen (1886), Cotton (1956), Bird (2005), amongst others, suggest dimensions in the order of several to tens of kilometres in length and hundreds of metres or several kilometres in width at the mouth. However, with inundation of tributaries of a river drainage system there will be decreasing size of inlets (rias) up-stream in a branching ria system. In this context, there should be no size limit to the definition of a ria, as the marine inundation of a river valley system can take place in both a highly branched system of a large river, with a wide range of valley sizes along the drainage network, or in a small river. If a smaller tributary of a large river, where marine-inundated, is considered to be part of the ria system, then an isolated marine-inundated small river should also be considered to be a ria, albeit a small ria.

As noted by Bird (2005), rias can vary in complexity of origin. For instance, the Galician rias are generally wide and deep marine inlets in valleys which may have been shaped partly by tectonic subsidence and the recession of bordering scarps. Subsidence has probably contributed to

the persistence of the ria in the mouth of Johore River in southeastern Malaysia, which remains a wide and deep inlet, whereas other Malaysian valley mouths have been infilled as alluvial plains, some with protruding deltas. Other rias persist because they were initially deep and sedimentary filling has been slow, as along the New South Wales coast (Roy 1984). In other respects, axiomatically, ria coasts can grade into deltaic coasts, estuarine coasts, and rocky shores with indentations. There are also complications in the concept, definition, and origin of a ria where existing rias have formed by marine submergence during the Holocene transgression but, as noted above, there have been several phases of valley incision during Pleistocene low sea-level phases, alternating with earlier ria formation during interglacial marine transgressions.

Although the definition of *ria* can be broadly translated to mean "river-valley marine inlet", generally to date, it has not comprehensively and descriptively included the type and relief of the terrain that has been inundated (*cf.*, review in Fairbridge 1968b). As a result, whether the marine-inundated river valley is deeply and narrowly incised (involving ravines and gorges), deeply and broadly incised, moderately incised, or bordered by a hinterland of relative low-relief, is unexplored. Thus, for example, without more refined designation as to "type of ria", or "type of ria coast", a low relief fluvially incised landscape, a moderate to high relief fluvially incised landscape, and a distributary channel system of a former abandoned Pleistocene delta, particularly if it is uplifted, strictly, would all qualify to be termed *ria coast*, and there is no current comprehensive system of descriptors or protocol to separate the types.

In the context of the review above, the coastal form of the Kimberley shores exhibit particular types of ria coast. Not consisting of isolated individual rias such as occurring along the coast of southern United Kingdom (*e.g.*, Kingsbridge Estuary in England), or Chesapeake Bay in the United States of America, the Kimberley Coast presents a ria coastline, consisting of innumerable rias of various sizes, shapes, and orientations. For much of its length the Kimberley Coast is strictly a marine-inundated river-cut landscape, comprised of marine-inundated river valleys and fluvially-cut ravines of varying sizes, depths, and valley orientation, widening towards seawards. These rias are filled with sediment to varying extent. For its south-western sector, however, the Kimberley Coast is a transverse ria coast (the Irish model) where the coastal morphology is the result of inundation of a ridge-and-basin topography developed from a fold belt oriented transverse to the coast. The Kimberley Coast also exhibits marine-inundated landscapes with trellis drainage patterns, that are part of the ria suite (because they are part of the fluvial drainage network that has been marine-inundated) but that are near-landlocked embayments and narrow inlets not fully open to the sea and/or not widening to the sea as would be expected in the traditional notion of a fluvially developed ria. These rias vary in orientation from coastal-transverse, to coastal-oblique, to coastal-parallel yet all are marine-inundated interconnected fluvial valley systems. As such, the coastal landscapes of the Kimberley Coast carry the notion of what constitutes a ria coast to an extreme of its definition and presents a wide range of intergradational

coastal forms of ria expression from megascale to microscale (the largest scale to small-scale), and from rias open and widening to the sea (sea-oriented in their gulf form) to those that are marine-inundated narrow (fracture-controlled) ravines to those that are near land-locked and land-oriented in their mouth. A summary of the types of rias developed along the Kimberley Coast, ranging from marine-inundated fluvially incised valleys to marine-inundated fracture valleys, will be described later to illustrate the scope of what constitutes a *ria* and a *ria coast* in this paper.

Background theory of geoheritage – scope, scale, and assessing significance

Prior to identifying and assessing sites of geoheritage significance along the Kimberley Coast, some background information is provided below, in terms of the theory underpinning geoheritage, classification of coasts to identify geodiversity of sites to assess geoheritage significance, the global approach of inventory-based site-identification and assessment, and the approach that has been designed in Western Australia to identify sites of geoheritage significance (*i.e.*, applying a Geoheritage “tool-kit”).

Globally, geoheritage (the recognition of the heritage values of geological features) has become important because it has been established that Earth systems have a story to tell, and that they are linked to the ongoing history of human development, providing the resources for development, and a sense of place, and have scientific, historical, cultural, aesthetic, and religious values (Brocx & Semeniuk 2007; Brocx 2008). In addition, Earth systems are the foundation of all ecological processes, and part of the heritage of our sciences (Torfason 2001). Geoheritage and geoconservation have become a significant means for preserving geological features of importance and can range in scale from very large to fine scale, in significance from International to local, and can encompass a wide range of geological/geomorphological features, or occur in isolation, or as an inter-related suite that should be conserved as an ensemble. A Geoheritage tool kit was designed to systematically address and assess this geodiversity (Brocx & Semeniuk 2009a, 2010a).

Since geoheritage and geoconservation are concerned with heritage and conservation of matters geological, *then all components of geology should be encompassed under its umbrella*. The term geoheritage is used as follows (Brocx & Semeniuk 2007):

Globally, Nationally, State-wide, to local features of geology, such as its igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogic, palaeontologic, geomorphic, pedologic, and hydrologic attributes, at all scales, that are intrinsically important sites, or culturally important sites, that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference.

The scope of geoheritage also involves identifying different categories of geoheritage significance, and all these categories can be recognised in the coastal zone (Brocx & Semeniuk 2007):

- type examples, reference sites or locations for stratigraphy, fossils, soil reference profiles, mineral sites, and geomorphic sites, including locations for teaching, research, and reference;
- cultural sites, *e.g.*, where classic locations have been described;
- geohistorical sites where there are classic exposures in cliff and outcrops where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed;
- modern, active landscapes where dynamic processes are operating.

Coastal geoheritage pertains to matters of geoheritage and geoconservation specifically in the coastal zone, an interface on the Earth's surface that is rich in geological and geomorphic processes and products because of the interaction geomorphically, sedimentologically, hydrochemically, biologically, and diagenetically, between land, sea, freshwater, and atmosphere (Brocx & Semeniuk 2009b).

Scale is important to consider in geoheritage and geoconservation because sites can range from landscapes and geological phenomena at montane-scale and orogen-scale to that of outcrops, bedding planes, or a crystal, *viz.*, megascale, macroscale, mesoscale, microscale, and leptoscale (Brocx & Semeniuk 2007). In many locations globally, geological sites are important because of crystal-sized phenomena and crystal fabrics, because it is often at this scale that the story of the Earth unfolds. At the next scale in increasing size, features of geoheritage significance, represented by outcrops and bedding scale features, include fossil sites, or Hutton's unconformity at Siccar Point (Brocx & Semeniuk 2007). Important geological and geomorphological features continue to occur in increasing scale, right up to the scale of mountain ranges, extensive landforms, and major drainage basins, such as Monument Valley Utah/Arizona, or The Grand Canyon in Arizona (Holmes 1966; Shelton 1966).

In this paper, the classification of coasts (Brocx and Semeniuk (2010b) and the Geoheritage “tool-kit” (Brocx and Semeniuk 2009, 2010a), has been used to identify and assess the geoheritage significance of the Kimberley Coast, using the descriptors for scale, *i.e.*, from megascale to leptoscale, as a means of assessing geoheritage significance, in association with criteria for levels of significance as follows::

- International: one of, or a few, or the best of a given feature globally;
- National: though globally relatively common, one of, or a few, or the best of a given feature Nationally;
- State-wide/Regionally: though globally relatively common, and occurring throughout a Nation, one of, or a few, or the best of a given feature State-wide or Regionally; and
- Local: occurring commonly through the world, as well as Nationally to Regionally, but especially important to local communities.

Coastal classification for purposes of identifying sites or features of geoheritage significance

Identifying sites or features of coastal geoheritage significance requires a number of steps beginning with classification of coastal geology and geomorphology and geoheritage category. As discussed by Brocx & Semeniuk (2010b), classifying coasts for geoheritage purposes is difficult due to the complexity, intergradation, and different scales at which coastal features are expressed, with variation potentially present locally or regionally, and with variation in expression of outcrop and cultural/historical content. While geological region and environmental setting play major roles in determining regional variation in coastal form and coastal products, or expression of geological content, coasts at the local scale commonly are expressions of a gradation of processes from (marine) inundation, to erosion, to deposition. Biogenic activity and diagenesis also play a role in forming coasts though they tend to be subdominant to the other processes. To address this geodiversity, coasts are classified by Brocx & Semeniuk (2010b) according to the products formed by the coastal marine five processes, *i.e.*, marine inundation, erosion, sedimentation, biogenesis, and diagenesis. However, some coasts are significant because they illustrate ancient geohistorical sequences, or manifest Holocene history geomorphically and stratigraphically. Twelve types of coastal forms and/or geological features developed in the coastal zone have been identified by Brocx & Semeniuk (2010b):

- Type 1 landforms developed by the post-glacial marine inundation of pre-existing landforms (the primary pre-inundated landscape is still evident)
- Type 2 landforms developed by marine inundation of pre-existing landforms and coastal erosion of the bedrock geology, or hinterland landforms
- Type 3 landforms wholly developed by coastal erosion, or where erosion has totally or nearly totally overprinted primary (pre-transgression) hinterland landforms
- Type 4 coasts developed by the exhumation or isolation of older landforms and their geological features
- Type 5 coastal landforms developed by marine inundation and sedimentary infilling
- Type 6 landforms wholly constructed by coastal sedimentary processes that have been active during the Holocene
- Type 7 landforms constructed by Holocene coastal sedimentary processes that have superimposed erosional features
- Type 8 biogenic coasts
- Type 9 coasts with dominant or conspicuous diagenetic features
- Type 10 erosional coasts recording Holocene sea-level history
- Type 11 Holocene depositional coasts recording sedimentary history, ocean history, climate history and sea-level history
- Type 12 sea cliffs exposing lithology, stratigraphic sequences and contacts, and structure

The classification of coastal types is not fixed to scale, and the various types are related to scale by a descriptor (Brocx & Semeniuk 2010b).

Identification of sites or features of geoheritage significance

There are a number of ways that sites of geoheritage significance may/can be identified. The literature provides a history of how this has been achieved, with a focus generally on significant geological features present in inland sites, or with a focus on geological content for science and education, or themes, with the final outcome being that globally, an ad hoc approach for conserving sites of geoheritage significance has been, or is being, replaced with an inventory-based approach (Doyle *et al.* 1994; Wimbledon *et al.* 1995, 2000; Wimbledon 1996; Fuertes-Gutiérrez & Fernández-Martínez 2010; for discussion see Brocx 2008). For instance, since 1949, the assessment and subsequent selection of sites in the United Kingdom has been undertaken on the basis of a series of blocks which may be based on time, subject or regional divisions, or combinations thereof. Building on this process, in 2001–2002 ProGEO contributed to a number of important geoconservation initiatives that included the incorporation of a policy statement relating to the importance of geology and physical landscapes in the Pan-European Biological and Landscape Diversity Strategy, and an alliance with the International Union of Geological Sciences and UNESCO for the purpose of compiling a European inventory for the Geosites project (ProGEO 2002a, 2002b, 2002c).

A systematic inventory-based approach to geoheritage and geoconservation requires a procedure, and identifying geological regions and what comprises the “geological essentials” of those regions provides the first step to developing such a procedure in order to identify the fundamental geological features for geoheritage/geoconservation (Brocx and Semeniuk 2010a). Clearly not all aspects of geology of the Earth are present in the one region, and clearly not all aspects of the geology of a given region will be of geoheritage significance – the former, for instance, recognises the unique occurrence, rarity, or representativeness of some geological features, and the latter requires some measure of assessment of significance.

The Geoheritage tool-kit, illustrated in Figure 4, provides the procedure to identify geological components across various geological sub-disciplines and at various scales, to assign geological sites to various conceptual categories of geoheritage, and to assess the levels of significance of the various geological features (Brocx & Semeniuk 2009; 2010a). These concepts assume that the wider definition of what constitutes ‘geoheritage’, as discussed in Brocx and Semeniuk (2007), is being applied. While initially developed for use in Western Australia, its principles and approach, in fact, have global applicability. The steps for identifying sites of geoheritage significance, using an inventory based approach, using the Geoheritage tool-kit are described below.

Step 1 – identify the geological region and environmental setting in which a site or feature occurs: The identification of geological regions and environmental setting provides a natural boundary to the

THE GEOHERITAGE TOOL-KIT

Step 1: determine/define the natural geological region in which the area or site resides (Western Australia, and the Kimberley region used here as an example)

Step 2: from literature, interviews, fieldwork, identify/list the characteristic, peculiar, important or essential geomorphic, stratigraphic, structural, mineralogic, petrologic, hydrologic, diagenetic, pedologic, palaeontologic, and other geologic features of the area to develop an inventory of geoheritage features

Step 3: assign each of the features identified in Step 2 to one of the categories of Geoheritage sites (Inset A)

Step 4: assign each of the features identified in Step 2 to a scalar frame of reference (Inset B)

Step 5: determine the level of significance of each of the features (Inset C)

Step 6: based on the range, category, inter-relations, and level(s) of the significance of the geological features, determine what type or what level of geo-conservation the area requires according to prevailing existing conservation categories

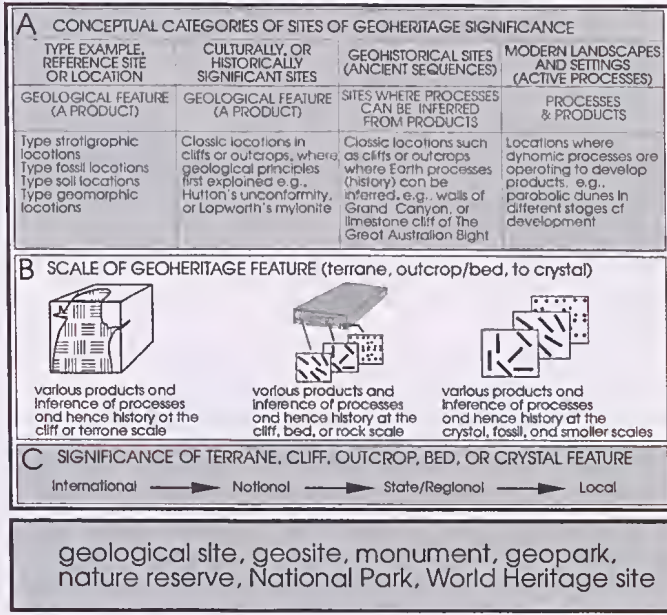
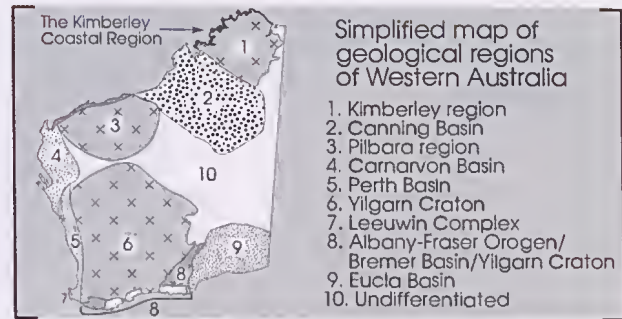


Figure 4. The Geoheritage tool-kit. Geological regions from Brocx & Semeniuk (2010b), and based on Geological Survey of Western Australia (1975, 1990), Playford *et al.* (1976) and Myers (1994).

area being investigated in terms of geological and geoheritage features, and provides an indication of the types of materials and styles of geological features and coastal features that may be expected. It also ensures that comparisons in assessing levels of significance are undertaken wholly within similar geological regions with similar history. Identifying the various geological regions, and then identifying features therein, therefore, is the first stage of a systematic inventory-based approach to developing a database for sites of geoheritage significance according to the scope placed onto geoheritage (i.e., all matters geological). This does not necessarily translate to just listing isolated sites of geoheritage significance but may also lead to the identification and linkages to interrelated ensembles of features. For Western Australia, this translates to recognising major cratons and basins cropping out at, or forming the coast, and the climatic/oceanographic setting of a coastal tract.

Step 2 – compile a list (or inventory) of features that characterise, or are peculiar to, or that are the essence of the area: Undertake literature reviews, interviews, and/or fieldwork an inventory is compiled of the geomorphic, stratigraphic, structural, petrologic, hydrologic, mineralogic, palaeontologic, diagenetic, pedogenic, and other geologic features that characterise, or are peculiar to, that are the essence of the area, or that already have

been recognised as important to that region. For instance, in the Kimberley region, the Precambrian rock types, features that illustrate their structural and metamorphic history, the Cainozoic ferricrete and laterite, and the landscape as related to geology, comprise the geological essentials of that region, and on the Nullarbor Plain, the Tertiary limestone, the coastal cliffs, the karst, the cave sedimentary deposits, the late Cainozoic surficial aeolian sand sheet, and wetlands would be identified. Specifically for coastal geoheritage, this step, at the largest scale, involves classification of the coast types developed by the five main coastal processes within a given region, and, at smaller scales, involves identifying smaller scale features particular to any coast within its regional setting.

Step 3 – allocate each of the components of the list, or ensembles of the components (developed at Step 2) to a conceptual category of geoheritage: Determine whether a given location is a reference site, a cultural site, a geohistorical site, or a modern active landscape so that comparisons in assessing levels of significance are undertaken within similar conceptual categories.

Step 4 – allocate the geologic features in the list to a specific scalar frame of reference: This is so that assessments of levels of (comparative) significance can be undertaken within similar scalar categories.

Step 5 – assess the level of geoheritage significance: Use of the definitions/criteria outlined above for each of the components of the list developed at Step 2 to assess significance. The next stage would be to locate the best known examples, regardless of scale, of these features or of inter-related ensembles of features.

Step 6 – determine what type and what level of geoconservation the area requires: After an assessment of the range, categories, inter-relationships, and level(s) of significance of the geological features, determine what type and what level of geoconservation is required.

Once the inventory of components and their level of significance of a study area are compiled (in this case, the Kimberley Coast), and enough geological features have been ranked as being of significance, or a few rank as being of high significance, sites of geoheritage significance can be proposed/proffered for geoconservation at a Regional, State, National or International level for one or a few of its components, or for the integrated ensemble of its components. If the latter, the area may qualify to be viewed as a geological park.

Definition of the Kimberley Coast

The geographic term “Kimberley” has been applied generally to the region of north-western Australia to include the upland area of the Kimberley Plateau, the Kimberley coast, the area east of the Kimberley Plateau such as Cambridge Gulf and its adjoining uplands, King Sound and Stokes Bay and their bordering uplands, the Dampier Peninsula, and the area of Broome. The geographic term, administratively and politically, even has been applied to areas as far south as Eighty Mile Beach along the Canning Coast. In terms of coastal geomorphology, coastal sectors, natural coastal units, and geology, the Kimberley Coast was restricted and defined by Semeniuk (1993) to refer to the highly indented coastline bordering the Precambrian massif of the Kimberley Basin, and its bordering Precambrian King Leopold Orogen. King Sound (including Stokes Bay) and Cambridge Gulf are excluded from the definition of the Kimberley Coast, and form adjoining coastal sectors (Fig. 5). This usage of Kimberley Coast is adopted here.



Figure 5. The location of the Kimberley Coast.

The Kimberley Coast is a rugged, dominantly rocky coastline with local sedimentary accumulations. Its coastal form is dominated by short rivers and creeks that have incised deep valleys into the regional high-relief plateau that is underlain by sandstone and basalt. The geological grain of the region, in terms of lithological trends, fold trends, faults, and boundary between the various geological units, such as between Precambrian rock massif and Phanerozoic rocks, and those within the Phanerozoic sequences, has been selectively eroded to form major valley tracts of the Fitzroy, May, and Meda Rivers and the Pentecost, Durack, and King Rivers. The southern to south-eastern margins of the Precambrian massif also has been incised by short rivers that form tributaries (deriving from the north) and deliver sediment to some of these larger rivers. As such, the complex of larger rivers that form the large gulfs are partly filled with sediments at their proximal portions, i.e., King Sound, Stokes Bay, and Cambridge Gulf, with voluminous sediment delivery from their respective large drainage basins. The short rivers with smaller drainage basins, that incise and *radially* rim the Precambrian rock massif along its south-western, western, northern, north-eastern coastal margin, form the ancestral architecture of the ria shores of the Kimberley Coast (see later).

Climate, oceanography, and coastal processes of the Kimberley region

The Kimberley region is located in a tropical monsoonal climate, spanning several broad climate subregions in terms of rainfall and evaporation (Trewartha 1968; Gentilli 1972). Following Gentilli (1972), the climate is tropical subhumid in the Cambridge Gulf area and northeast Kimberley area, tropical humid in the Drysdale River to Collier Bay area, with high rainfall centred on the Port Warrender area, tropical subhumid from Collier Bay to northern King Sound, and tropical semi-arid in the King Sound area (Fig. 6). Coastal rainfall influences local freshwater seepage, the extent that saline high-tidal flats are developed, and the development of beach rock, and evaporation determines the extent that saline high-tidal salt flats are developed. Wind in the region generates local wind waves that affect shore processes, mobilises sand into dunes, driving landward ingress of parabolic dunes, and causes evaporation of high-tidal salt flats. Wind is variable regionally (Fig. 6). The hinterland climate is important in that rainfall in drainage basins of the Kimberley Plateau determines the extent of run-off into rivers and the amount of freshwater and sediment delivered to the coastal zone. In general terms, the hinterland and the drainage basins of rivers and creeks that feed the coast zone with freshwater and sediments are largely located in semi-arid to subhumid climate.

The coastal zone of the Kimberley region is subject to four main oceanographic processes: semi-diurnal tides, wind waves, prevailing swell, and cyclones (Davies 1980; Semeniuk 1993; Lough 1998; Short & Woodroffe 2009). All of these processes are influential in coastal processes but some are environmentally/geographically restricted and some, such as cyclones and wind waves, are seasonally specific. As such, oceanographic processes are variable in their coastal effects across the region.

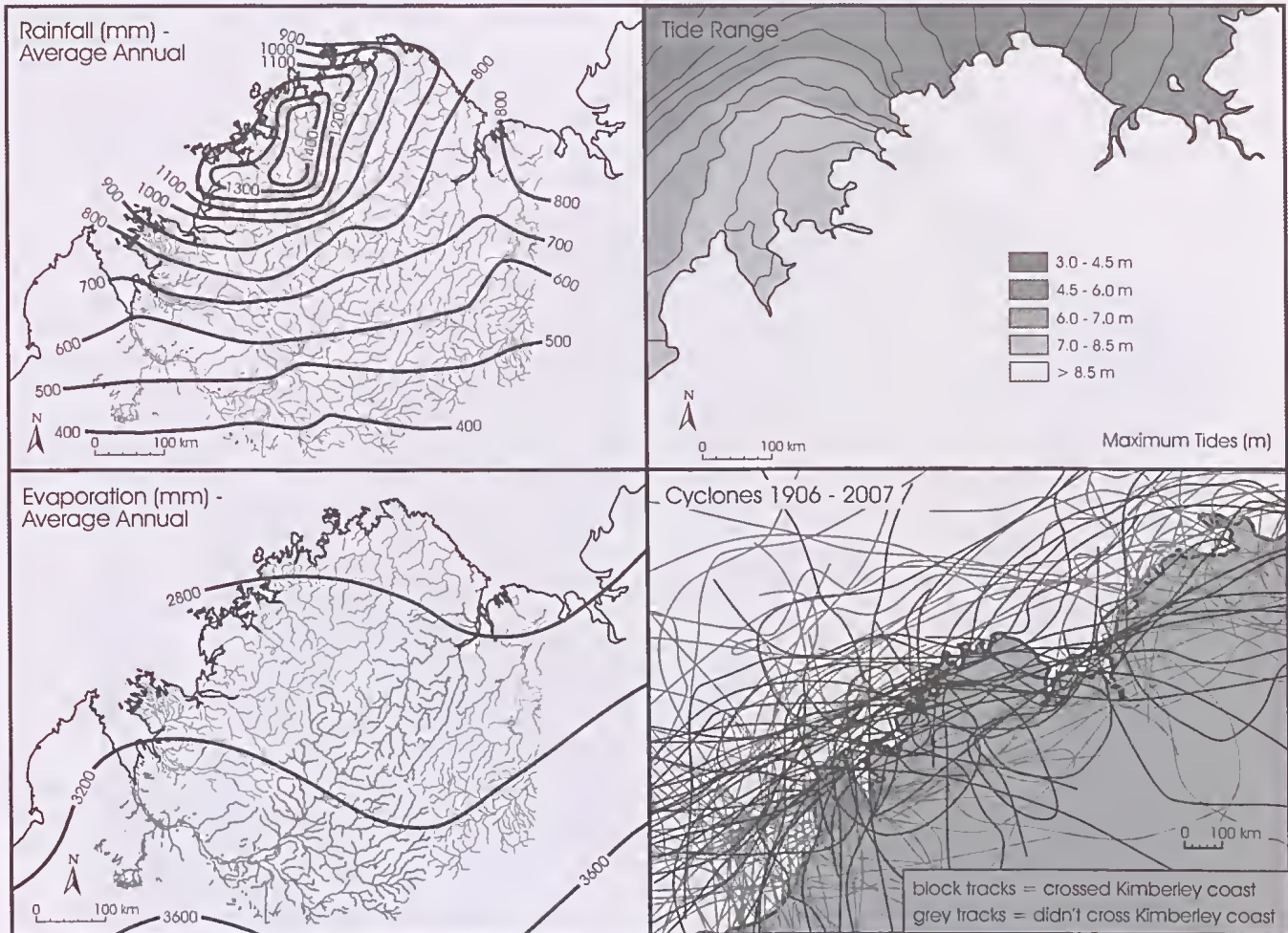


Figure 6. Rainfall, evaporation, tides, and cyclone tracks in the Kimberley region. (Climate data from Bureau of Meteorology 1973, 1975, 1988, 2010; tide data from Anon 2004). Map of average annual rainfall shows the extent of rainfall centred on the central north-western Kimberley Coast and its hinterland, and the decline in rainfall to north-east and south-west and the amount of rainfall that will recharge the drainage basins. Map of evaporation shows high evaporation across the northern coast, increasing southwards. Tide ranges are macrotidal in the area of King Sound to Prince Regent River, and Cambridge Gulf, decreasing to mesotidal in the area of Drysdale River to Cape Londonderry. The tracks of cyclone show those that intersected the coast and those that passed offshore – the former having direct impact on the coast, the latter distally generating impacts by wind, waves, and high seas.

Additionally, the shores of the Kimberley Coast are highly indented comprising south-facing, west-facing, and north-facing inlets and embayments and, in many cases, they are nearly wholly isolated from the open sea, being connected only by narrow channel-ways or waterways. As a consequence, parts of the Kimberley Coast, while subject to inundation by high tides, storm surges and cyclone-induced high-water, are protected from the action of wind waves, swell, and storm waves.

The coast of the Kimberley region is semi-diurnal macrotidal with local areas that are mesotidal (Fig. 6), and tides are a major feature of the coast in that they are pervasive regardless of its geometry, degree of shelter, and orientation (Semeniuk 2011), *e.g.*, all coastal forms from exposed sandy coves to large open embayments to narrow secluded ravines to tidal inlets and lagoons are influenced by the tide. Spatially, the next important coastal processes are wind waves and swell. Wind waves also are pervasive even in areas sheltered from swell where there is enough fetch oriented in relation to wind directions, but they are more seasonal, reflecting the

seasonality of wind patterns. Wind waves are effective where coasts are relatively exposed and, depending on fetch, they have variable effects on sedimentation, coastal processes, and erosion. Hence, while wind waves are region-wide, they have most influence where headland and coves face the wind/wave direction, or where small islands act as foci for sedimentation. Swell is a year-round phenomenon, deriving from northerly to south-westerly sectors, impinging on exposed coasts that face these directions. Swell is dampened and refracted as it interacts with the shelving near-shore shelf, and it enters fracture-aligned deeply embayed rias. However, swell is not a major wave type in the region. Cyclones are inter-annual and restricted to the summer season, and highly localised in their effects on the shores (Lourensz 1981; Lough 1998). They result in high seas, large waves and storm surges. During cyclone activity, there is winnowing of existing sedimentary deposits, transport and emplacement of sediments at storm levels above and well above the high tide mark, and coastal erosion. With massive influx of freshwater into the coastal zone during

cyclones, there is sediment delivery from rivers/creeks to the high-tidal alluvial fans and delivery of freshwater to the coastal zone.

The geology of the Kimberley Region

The hinterland of the Kimberley Coast (*sensu* Semeniuk 1993) is a massif of Precambrian rock. Though involving *circa* 160,000 square kilometres, this Precambrian geology is relatively simple in disposition of the major rock types and array of tectonic units. It comprises two main terranes (Griffin & Grey 1990a, 1990b; and Fig. 7): 1. the Proterozoic Kimberley Basin, which dominates the Kimberley region inland and along the coast; and 2. a semi-circumferential belt of Proterozoic folded and faulted rocks (granites and other intrusive rocks, gneisses, porphyries, metamorphic rocks, meta-sedimentary rocks, and volcanic rocks, with locally in-folded sedimentary rocks of the Kimberley Basin) referred to the King Leopold Orogen (a faulted and folded north-west trending belt bordering the south-west margin of the Kimberley Basin) and the Halls Creek Orogen (bordering the Kimberley Basin to the east).

Region-wide, five major lithological sequences of sedimentary and volcanic rocks, Proterozoic in age, accounting for a stratigraphic thickness of some 5000 m and assigned to Formational and/or Group level (as described below) comprise the stratigraphy of the Kimberley Basin (Griffin & Grey 1990b). From the base, they are: 1. the quartzose sandstones, feldspathic sandstones, minor siltstones, and minor acid volcanics of the Speewah Group (1000 m thick); 2. dominantly quartz and feldspathic sandstones (with local siltstone and dolomite) and basalt of the Kimberley Group (2000–4000 m thick) comprising (from the base) the King Leopold Sandstone, the Carson Volcanics (dominantly basalt), the Warton Sandstone, the Elgee Siltstone, and the Pentecost Sandstone; 3. siltstones, and sandstones of the Bastions Group (1500 m thick); 4. the Crowhurst Group; and 5. the Colombo Sandstone. Sandstone, in fact, dominates the rock sequences of the Kimberley Basin. Intrusive mainly into the Speewah Group and to some extent into the Kimberley Group is the multiple sill complex of the Hart Dolerite, with a combined thickness of 3000 m thick (Griffin *et al.* 1993). Locally in the south-western part of the Kimberley region, and specifically in the area of the King Leopold Orogen, there is outcrop of the Yampi Formation (formerly the Yampi Member of the Pentecost Sandstone; Tyler & Griffin 1993) comprised of feldspathic and haematitic sandstone and minor siltstone that forms coastal terrain in the Raft Point to Yule Entrance area.

The rocks of the Kimberley Basin are largely horizontal or near-horizontal throughout the region, but they have been gently warped about on fold axes oriented in two main directions (north to north-east, and west to north-west) that are widely spaced and result in broad dome-and-basin interference structure on the scale of (25–) 50–75 km (Griffin & Grey 1990b), such that the surface geology presents several rock belts oriented NNE generally younging eastwards (Fig. 7). The major rock sequences, identified to Formational and Group level in Figure 7, thus form generally NNE-trending belts that consequently crop out at the coast in laterally extensive rock formations. The Precambrian rocks also are

fractured and faulted, with some major faults and many minor faults oriented in the directions of the fractures. Faults in the Kimberley Basin trend north-west, north-east, and north, with the north-west trend having a major effect on drainage and coastal landscape. The fracture system is prominent, and is rhomboidal to orthogonal in configuration.

The rock sequences of the Kimberley Basin, as outlined above, relate to the Proterozoic rocks that underlie the entire Kimberley region, but the rock formations and lithologies *actually* cropping out at the coast are relatively more limited. In order of extent of outcrop, the main rock formations at the coast are: the King Leopold Sandstone, the Warton Sandstone, the Carson Volcanics, and the Pentecost Sandstone (Fig. 7). Thus, most of the coast is dominated by sandstone and some basalt of the Kimberley Group. Folded and faulted rocks of the King Leopold Orogen involving folded/faulted rocks of the south-western part of the Kimberley Basin and some metamorphic rocks and intrusions underpin the major coastal forms in the south-west of the Kimberley region. Though the Hart Dolerite is largely confined to inland outcrops, there is very local and minor expression of this formation at the coast. The rocks of the Speewah Group, Bastions Group, Crowhurst Group, and the Colombo Sandstone do not find (extensive) expression at the coast.

Parts of the Kimberley Plateau, and particularly where there is occurrence of basalt, are underlain by Cainozoic laterite and/or bauxite. These form resistant high-elevation plateaux and, where eroded, mesas.

A fuller account of the geology of the Kimberley Basin, King Leopold Orogen, and Halls Creek Orogen can be found in Veevers *et al.* (1970), Allen (1971), Gellatly & Sofoulis (1969, 1973), Gellatly (1971), Williams & Sofoulis (1971), Griffin (1990), Griffin & Grey (1990a, 1990b), Ruddock (2003), and Hassan (2004).

Landscape, rivers and valleys as architecture to the Kimberley coastal region

The landscape of the Kimberley region has been described by previous authors at a regional scale or at a reconnaissance level or as a background to geological studies (in the citations above), but not to any detail or emphasis for use in interpreting coastal landforms. For completeness they are cited here; they include Jutson (1950), Speck (1960), Speck *et al.* (1964), Mabbutt (1970), Jennings & Mabbutt (1977), and Pilgrim (1979).

The coastal forms in the Kimberley coastal region have been determined by the lithology and structure of regional geology, interfaces between major geological units, by marine inundation of onshore landforms, by the sizes, shapes and configuration of rivers, creeks, their tributaries, and other valley tracts in the region as controlled by the geology, and by local Holocene sedimentation such as mud accretion, and beach, spit, barrier and dune development.

Underlying patterns to hinterland landforms and to coastal forms developed from them are the horizontal nature of the dominant lithologies, the fault/fractures in the region, and the orogenic fold belt. Within the context

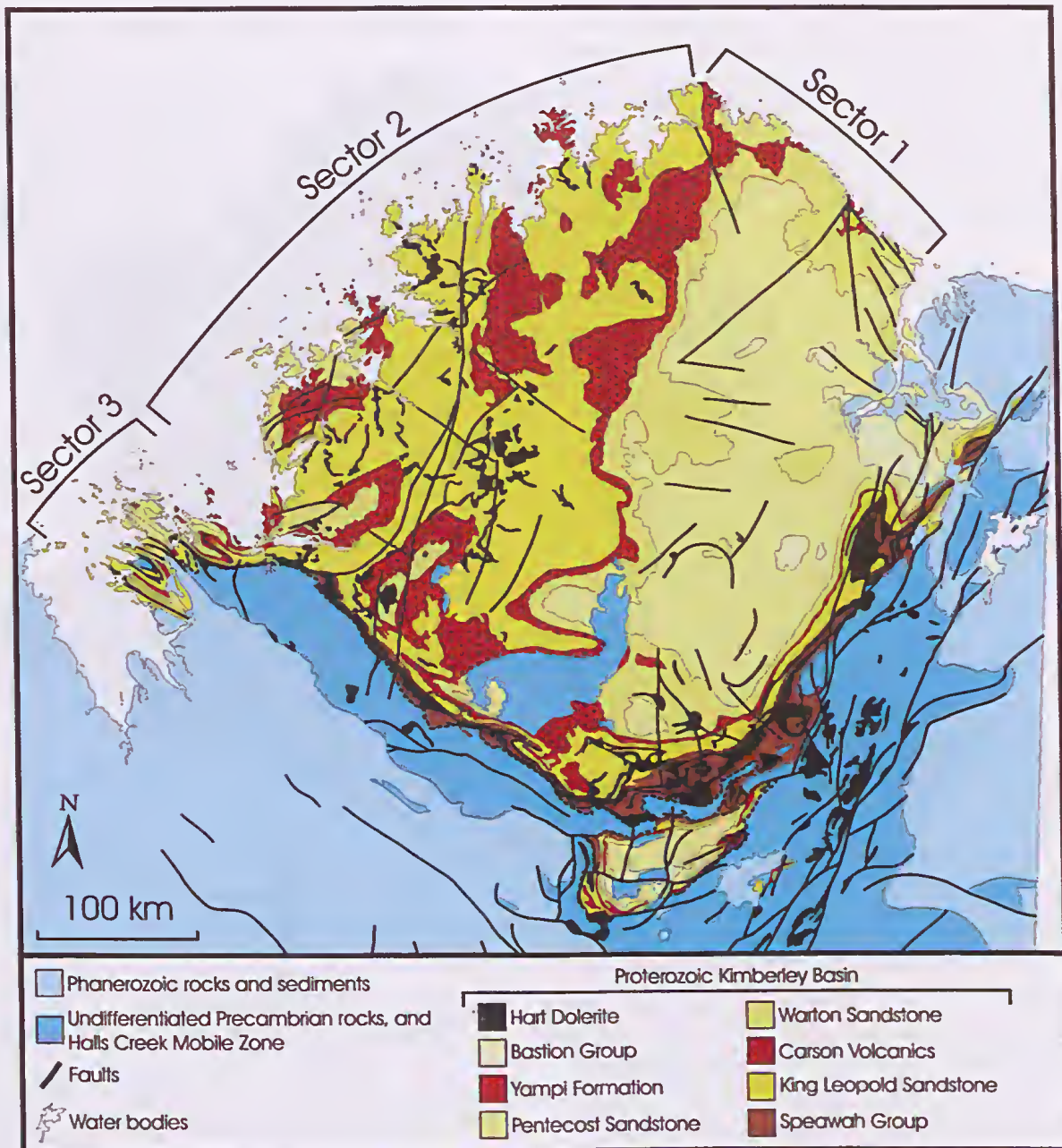


Figure 7. Geology of the Kimberley region (from Myers & Hocking 1988, with additions from Hassan 2004), and the sectors of the Kimberley Coast determined by geology.

of the sandstones and basalts that lithologically dominate the Kimberley region, structurally there are eight main determinants of landform expression of ridges, spurs, plateaux, ravines, and valleys:

1. the sandstone-dominated terrain of the inland Kimberley region, composed of relatively flay-lying lithologies, is essentially a dissected plateau with mesas;
2. the basalt-dominated terrain of the inland Kimberley region, composed of basalt, also is a dissected plateau with mesas;
3. the felspathic and haematitic sandstone terrain of the Yampi Formation, which forms a dissected, rounded topography;
4. the warp (fold) axes that have resulted in the local doming of the plateau and in west-oriented

drainage and northwest to north-oriented drainage;

5. major NW-oriented faults;
6. regional rhomboidal fractures, mainly in the sandstones, and thus NW, NE oriented smaller valley and ravines;
7. the King Leopold Orogen fold belt that results in WNW-oriented ridge-and-basin topography;
8. geological/lithological contacts, and contacts between terranes, that result in NNE-oriented and N-oriented embayments.

As a result, there are a number of drainage basins deriving from the main water sheds developed in the region (Fig. 8), and drainage patterns in the Kimberley region that will determine coastal forms, the nature of

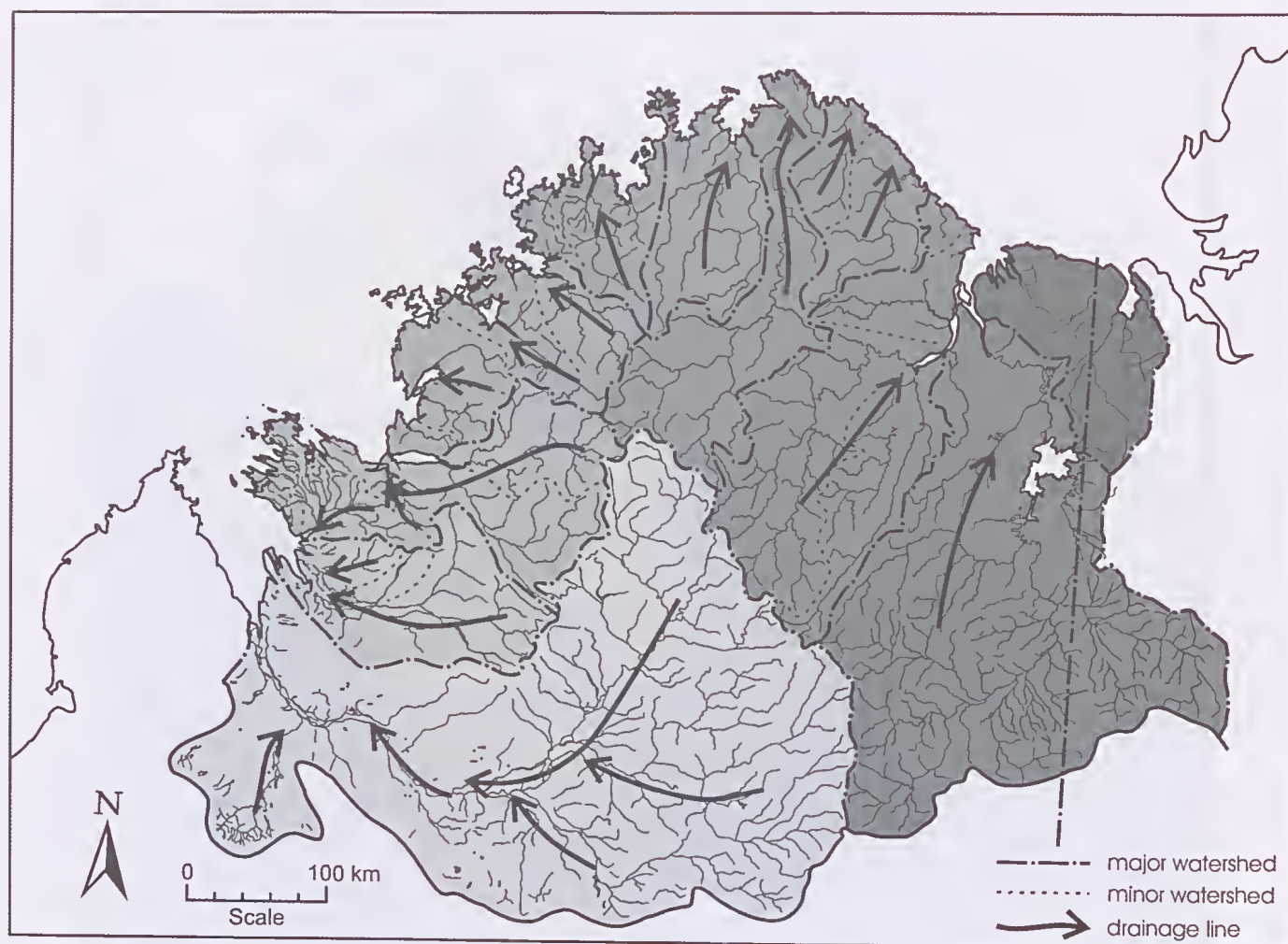


Figure 8. Kimberley region rivers and drainage basins (from Department of Water 2006).

the gulfs in the region, and the size of the drainage basins (which in turn determines the amount of sediment delivery to the coast). These drainage basin patterns are underpinned by the regional geology and structure, and by smaller scale structural features. The margins of the drainage basins define the various water sheds in the Kimberley region, and help place the size of the fluvial systems into perspective. A description of the drainage patterns is provided below. Across the region, the variability in size of drainage basin, the lithologies where the drainage basin resides, and the rainfall results in variation of sediment volumes and particles types delivered to the coast.

The drainage basins of the Durack, Pentecost, and King Rivers derive from a watershed to the west, south, and partly from the south-east. Cambridge Gulf, the confluence of these river systems, is located along the contact of Precambrian rocks and Phanerozoic rocks. The Durack, Pentecost, and King Rivers are medium-sized rivers, and the margins of their drainage basins to the west define the water shed of the Kimberley Plateau. The northern part of the Kimberley Plateau has only small watersheds and a plethora of small rivers, rivulets, creeks, and ravines following the fracture patterns of the bedrock. The north-western to western part of the Kimberley region, extending from the Drysdale River to Collier Bay, encompassing the Drysdale River, Mitchell

River, and the Prince Regent River, is comprised of a series of medium rivers and small rivers that derive from water sheds centred on the Couchman Range and Mount Keating area that asymmetrically partition the Kimberley Plateau into western and eastern portions. Drainage trend semi-radially westerly to north-westerly to the coast. The south-western part of the Kimberley Coast is the marine-inundated fold-and-basin system of the King Leopold Orogen. Here, the basins form marine-inundated inlets, and also form the valleys for short rivers. The Fitzroy, Meda and May Rivers, at their distal ends, have carved out a large valley tract between the Precambrian massifs and the Phanerozoic rocks, and have also followed the faults and tectonic grain within the Phanerozoic rock sequences; they have their headwaters located in terrain developed on the folded, faulted, and fractured system of the southern margin of the Precambrian massifs, with the Fitzroy River also draining areas to the south in the McLarty Ranges.

The drainage basin systems and their seaward expression as ria coasts, together with the rocks cropping out at the coast, define three main sectors of the Kimberley Coast, (Fig. 7):

- Sector 1 – the coast between Cape Dussejour and Cape Londonderry: dominated by sandstones;
- Sector 2 – the coast from Cape Londonderry to Collier Bay: dominated by sandstones, but also

with outcrops of basalt, siltstone, and haematitic sandstone;

Sector 3 the extension to the coast of the King Leopold orogenic fold belt.

These coastal sectors also define distinct tracts of coastline in the Kimberley region. Sector 1 is dominantly a straight coast cut mainly into Warton Sandstone, with development of small ravines, small coastal indentations, and some embayments formed by medium rivers. Sector 2 is a highly indented coast cut mainly into King Leopold Sandstone, as well as into the Carson Volcanics, Warton Sandstone and local Hart Dolerite, with development of macroscale to mesoscale embayments formed by large rivers and tide-dominated deltas and mesoscale embayments, as well as sections of straight coast with small ravines, small coastal indentations. Sector 3 is a highly indented coast formed by marine-inundation of the ridge-and-basin topography of the King Leopold Orogen comprised of a variety of folded formations (including the King Leopold Sandstone and Warton Sandstone), with development of mesoscale to macroscale embayments, as well as sections of straight coast with small ravines and coastal indentations. Local outcrops of volcanic rocks near Cape Londonderry and at Port Warrender provide smaller scale variations of coastal morphology to the any of the dominant patterns of the main sectorial patterns.

The dominating landscape feature of the onshore and coastal Kimberley region of course is the Kimberley Plateau, a terrain that is underlain mainly by fractured Precambrian sandstone with some basalt, and since the fractures and faults are prominent, they have a major influence on development of the onshore landscape and coastal geomorphology. Sandstones form a high relief plateau, with elevation of ~600 m to 300 m, falling to 200 m to 100 m at the coast. They are deeply incised by rivers and creeks, with channel margins of steep-sided ravines, bluffs, cliffs, and associated mesas. A landscape of steep-sided ravines, with bluffs and cliffs, and mesas, with variable sheer rocky surfaces, or scree, or colluvium presented at the coast, results in steep rocky shores, highly indented coastlines, bouldery shores, and nearshore or intra-ria islands (usually marine-isolated mesas). Three types of coast are developed: 1. those where the bluffs and cliffs are directly presented at the shore, thus forming steep rocky shores; 2. those where the cliffs, other high-relief landforms, and mesas are set back from the shore or have been stranded by coastal progradation, *e.g.*, Mount Trafalgar in the coastal zone of the Prince Regent River area; and 3. those comprised of a dissected plateaux and mesas thus forming ria tracts with intra-ria nearshore islands, *i.e.*, marine-isolated mesas. The cliff lines of the latter coasts are often bordered by tidal sedimentary deposits, or by aprons of colluvium, or themselves frame ribbons of sedimentary deposits.

The fluvial courses have been controlled by the faults and fracture patterns and, consequently, the valley tracts are straight, to rectangular (orthogonally) and rhomboidally branching. For instance, the Prince Regent River, a large straight river, follows a major fault/fracture, and its associated creeks and tributaries exhibit a trellis drainage pattern following the fracture patterns in the sandstone-dominated region. Many of the other

rivers, creeks, and valley tracts exhibit the same geometry by following fracture patterns, exhibiting trellis drainage and criss-crossing valley tracts. In the coastal zone, where these rivers, creeks, tributaries, and valley tracts have been inundated by the post-glacial transgression, the mainland coast consists of fracture-aligned gulfs, embayments, inlets, and narrow ravines. The coastal embayments show the same style of geometry as the trellis drainage of the sandstone hinterland.

Where the Kimberley Plateau is underlain by basalt, or by felspathic and haematitic sandstone, while still exhibiting topographic elevation, the landscape and drainage are more moderate, and drainage is dendritic, with less control by fractures, and rivers, creeks, and their tributaries derive from landscapes that exhibit rounded topography. This terrain is commonly underlain by laterite which forms plateaux. Where basalt, or felspathic and haematitic sandstone front the coastal zone, the topography forms rounded coastal headlands, and broader embayments, and the rivers, creeks, tributaries, and valley tracts form more open embayments, *i.e.*, the coastal embayments show the same style of geometry as the moderate landscape and dendritic drainage of the hinterland. Where lateritic plateaux are exposed at the shore, the coast is comprised of plateau-edge cliffs backing the shore, locally with mesas forming nearshore islands or intra-ria islands. The contrast between coastal forms developed on fracture sandstone, basalt, and felspathic and haematitic sandstone is shown in Figure 9.

The King Leopold Orogen, as a tightly folded sequence of rocks, with fold axes oriented WNW and cross-cutting fractures, geomorphically forms ridge-and-basin topography of WNW-striking linear ridges (the fold limbs) and associated valleys. Minor, rivers, creeks, and their tributaries have followed the dominant grain of the geological structure, with smaller tributaries and feeder valleys following the cross-cutting fractures. Marine inundation of this topography has resulted in prominent WNW-striking peninsulae (at various scales), WNW-striking inlets, embayments, and lagoons, WNW-oriented chains of islands as small local nearshore island (archipelago) complexes (*viz.*, the Buccaneer Archipelago), isolated or near-isolated linear high-tidal marine enclosures and, where fracture has influenced cross-oriented drainage, trellis-shaped embayments and inlets.

Boundaries between major geological units, major faults and fractures, and tectonic grain, and/or a location with a geological unit, have been the control for development of some major rivers (compare Figure 7 with Figure 8). Following the post-glacial transgression, the seaward expression of the major rivers are large gulfs and inlets. As noted earlier, the Prince Regent River follows a major NW-trending fault. The Fitzroy, May and Meda Rivers have carved valley tracts following the geological strike of lower Phanerozoic rocks and, in part, the boundary between Precambrian and Phanerozoic rocks. The drainage basins of the Pentecost, Durack and King Rivers, terminating in the funnel-shaped Cambridge Gulf, have been localised in, and controlled by, the folded and faulted terrane of the Halls Creek Orogen.

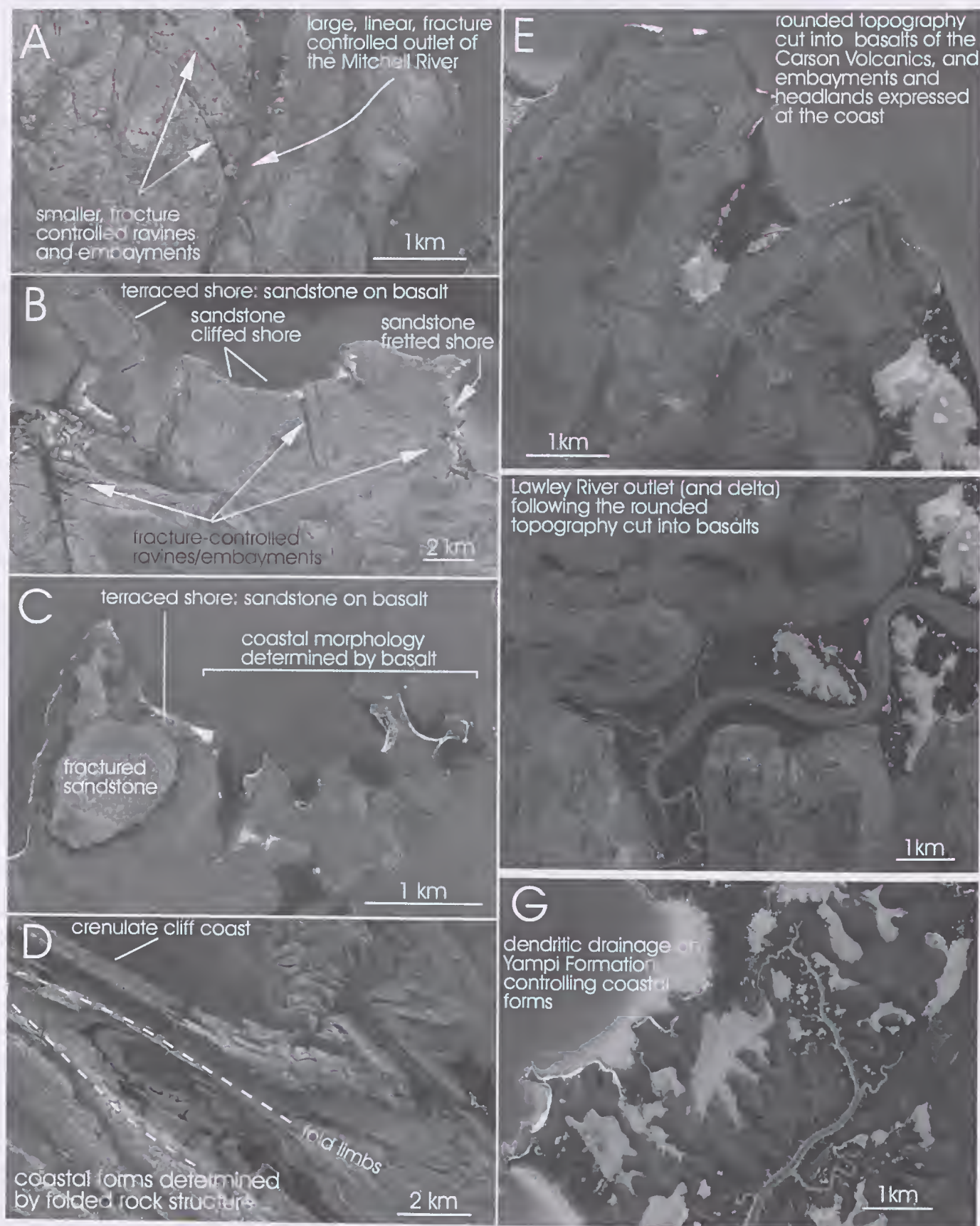


Figure 9. Annotated aerial photographs showing contrast between coastal forms developed on fractured sandstone, basalt, felspathic and haematitic sandstone, and folded rocks, with fracture-controlled ravines and embayments, and terracing controlled by the stratigraphy. Images from Google Earth.

The nature of ancestral (pre-Holocene) topography or landforms in the Kimberley region that were inundated by the post-glacial transgression to develop the modern coastal landforms, such as gulfs, embayments, inlets, archipelagos (*viz.*, the inner part of the Buccaneer Archipelago and the Bonaparte Archipelago, and the Eclipse Archipelago) and ocean-facing cliffs, is another factor that determines what landforms and what types of deposits are generated at and within the coastal zone. In other words, coastal forms along the Kimberley Coast have been determined by the nature of the onshore landforms, their underlying geology and the interfaces between major geological units, and by the sizes, shapes and configuration of rivers, creeks, their tributaries, and other valley tracts in the Kimberley region. Ancestral topography and geology also determine the size of embayments, their shape, their orientation, whether they have been fluvially derived, and whether the indented coast grades into or is adjoined by an archipelago. Since hinterland geology is dominated by sandstone plateaux, bluffs, cliffs, aprons of scree at the foot of the bluffs/cliffs, and blankets of scree covering the rocky slopes and ridges, these form the foundation to the coastal form of the Kimberley Coast.

In the context of the geology/geomorphology described above, there are eleven coastal forms occurring along the Kimberley Coast, some of which represent the types of rias in the region, ranging from marine-inundated fluvially incised valleys to marine-inundated erosional valleys, illustrating the scope of what is a *ria* and a *ria coast* in this paper; the coastal forms are:

1. Large funnel shaped gulfs
2. Large narrow v-shaped gulfs
3. Large broad embayments
4. Medium-sized to small narrow v-shaped ravines and valleys
5. Medium-sized to small embayments and coves
6. Isolated inlets and lagoons
7. Rectilinear to rhomboidal intersecting embayment/inlet complexes
8. Archipelago-and-embayment complexes bordering the Kimberley Plateau
9. Archipelago-and-inlet complexes bordering the King Leopold Orogen
10. Straight rocky shores
11. Scattered islands in an archipelago

A selection of these coastal forms are illustrated in Figure 10.

Depending on the orientation and oceanographic aspect of these coastal forms, they experience a gradation of wave and tidal energy, and hence determine or influence the nature and style of sedimentary accumulations. They may be exposed to prevailing swell and wind waves and thus subject to high energy of waves and tides. They may be relatively protected from prevailing wave action and subject mainly to tidal currents. Or they may be fully protected from wave action and only inundated on the highest tide (at times of near slack-water and slack-water) and thus oceanographically of low energy. The nature and style of sedimentary accumulations is also determined by how much sediment is delivered to or generated at the coast.

The coastal landforms, derived from marine inundation of the ancestral landforms, form the template for local Holocene sediment deposits that also contribute to coastal landform development through mud accretion on tidal flats, and beach, spit, barrier and dune development (Coastal Types 5, 6 and 7 of Brocx & Semeniuk 2010b). The sedimentary deposits along the Kimberley Coast are described by Semeniuk (2011), and a summary list is provided below. The sedimentary deposits form natural packages that are grouped into eleven suites reflecting their coastal setting, sediment types therein, processes, and stratigraphy; The simplest stratigraphic packages are ordered in a general manner from coarsest sediment and high-energy-emplaced to the most fine grained deposits, *i.e.*, from tempestites to mud tidal flat systems. The exceptions to this list, relating to energy spectrum, are the ria and embayment systems and bar-and-lagoon systems, which, as noted above, are complex ensembles of sediments. The stratigraphic packages are:

1. Tempestites
2. Block, boulder and gravel shore deposits
3. High-tidal alluvial fans
4. Tombolos and cusped foreland deposits
5. Beach cove deposits
6. Barrier sand/gravel deposits
7. Beach-ridge deposits
8. Sand-and-mud tidal flat systems
9. Mud tidal flat systems
10. Ria and embayment systems
11. Bar-and-lagoon systems

However, Semeniuk (2011) focused only on sedimentary material in the region, and not on Holocene indurated materials along the Kimberley Coast. Geologically important, and of geoheritage significance there are three other types of Holocene coastal materials; these are:

1. Fringing algal reefs
2. Fringing coral reefs
3. Beach rock

The algal reefs are shore-fringing boundstones (term after Dunham 1962, referring to accretionary deposits of skeletal organisms that form rigid carbonate structures). The algal boundstones (reefs) are deposits that encrust rocky shores at low tidal levels. They have fringing pavements up to 100 m wide, extending seawards from the rocky shore cliff. Structurally, they are composed of grossly layered skeletal boundstones with numerous platy to irregular cavities. Biologically, they are composed mainly of calcareous algae, with scattered small corals, embedded bivalves, lithophagic bivalves, interlayered and encrusting serpulid worm tubes, other worm tubes, bryozoans, hydrozoans, and sponges. Details of these fringing algal reefs will be described in a later publication.

The fringing coral reefs also are shore-fringing boundstones that encrust rocky shores at low tidal to subtidal levels, but are coral-dominated. Coral and calcareous algae have built fringing coralline structures extending seawards from the fringing algal reefs. Structurally, they also are composed of grossly layered skeletal boundstones with numerous platy to irregular

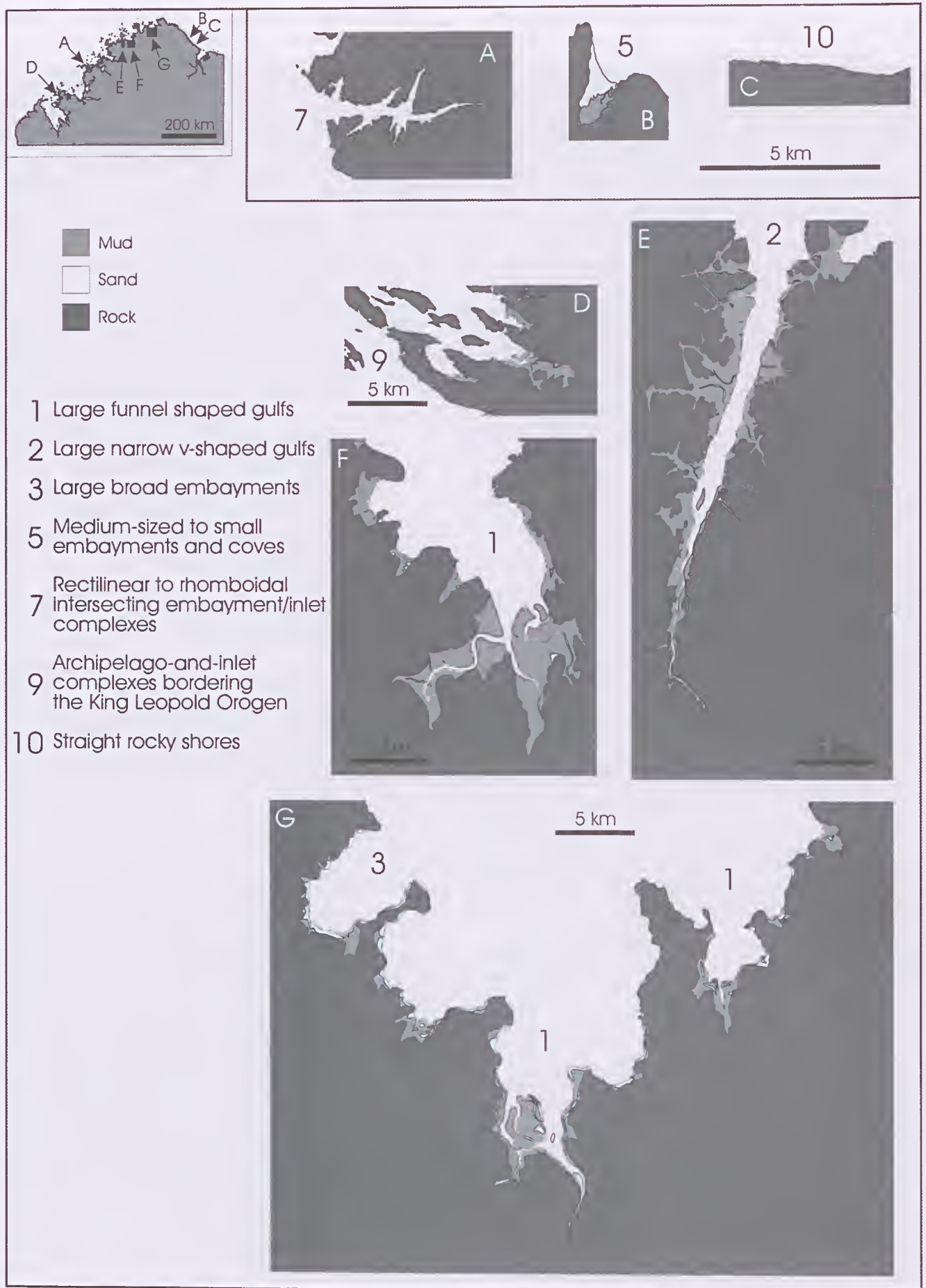


Figure 10. Major coastal forms of rias along the Kimberley Coast showing the variation in their size and shapes, annotated with the style of sedimentary deposits occurring within them. Bar scale for A, B, C, D, E, F & G is 5 km. The numbers refer to one of the eleven coastal forms mentioned in the text, and the letters A, B, C, etc. show the location of the example along the Coast.

cavities. Similar to algal reefs, biologically they are composed mainly of interlayered corals and calcareous algae, with embedded bivalves, lithophagic bivalves, and interlayered and encrusting serpulid worm tubes, other worm tubes, bryozoans, hydrozoans, and sponges.

Beach rock occurs in numerous locations along the Kimberley Coast. This is slope-parallel indurated beach sediment in the tidal zone (as sand or shelly beach sand or beach gravel), and can form beach-rock shore.

Essentials of the geoheritage features of the Kimberley Coast

The Geoheritage tool-kit has been used to identify sites or features of geoheritage significance on the Kimberley Coast, following steps 1–5 outlined earlier. Beginning with Step 1, the context for the ria coast is the Kimberley geological region and tropical macrotidal setting. The essential features are then identified and described, and their significance assessed. The assessment of the essential geoheritage features along the Kimberley Coast with respect to International, National and State-wide/Regional significance, together with the rationale for that assessment, however, the focus is on features that are International to National in geoheritage significance. The criteria used to assign a level of significance to a geoheritage feature have been outlined earlier (following Brocx & Semeniuk 2007).

From a consideration of the geology and geomorphology of the Kimberley Coast, the features that comprise the “geoheritage essentials” of the Kimberley Coast are listed in Table 1. The key features of geology and geomorphology, at various scales from megascale to microscale, are described below with respect to their main characteristics, the category of the geoheritage site, and the scale of the feature. Given the size of Kimberley Coast, it is beyond the scope of this paper to address key coastal localities that illustrate smaller scale features such as inter-formational stratigraphic relationships and other geological relationships, any good exposures of significant lithologies or sedimentary structures, and any mineral (crystal) outcrops. The ironstones at Yampi Sound are an example of this, in that they represent, within the King Leopold Orogen, a particular style of ironstone development replete with intra-formational stratigraphic and lithological relationships, ironstone structures, and post-mineralisation metamorphism (Gellatly 1972). Identifying key localities of these ironstones along the (natural) coast, as distinct from quarry exposures, to illustrate their features of geoheritage significance in their setting of Proterozoic age and structural/metamorphic history would involve numerous sites at a scale of enquiry beyond what is presented in this paper. The same effort of identification of sites would need then to be applied to the other rock types of the King Leopold Orogen and to the sedimentary, volcanic, and intrusive rocks of the Kimberley Basin. For the latter, for instance, there are numerous locations along the coast where there are excellent exposures of sedimentary structures and conglomerate beds within the sandstones, structures within the mudstones, contacts between the sandstones and mudstones and igneous rock structures within the volcanic rocks, amongst others. For this reason, we have

largely focused on the larger scale features of geoheritage significance along the Kimberley Coast, and leave the identification of the smaller scale features for a later study.

Many sites of geoheritage significance along the Kimberley Coast also have cultural significance to the Traditional Owners of the Mayala, Dambimangari, Uunguru and Balangarra peoples, *e.g.*, coastal freshwater springs, rock formations of spiritual value, cliffs, and coastal landscapes linked to ecology. It is beyond the scope of this paper to identify such sites and, further, in terms of ethics, we do not consider that it our place as Western scientists to identify such areas within the Kimberley region. However, many of the areas assigned to specific geoheritage categories in the text below from an Earth Science point of view could also be assigned to one of Cultural Significance from the perspective of the Traditional Owners of the region.

In the list of geoheritage essentials of the Kimberley Coast, shoreline indicators of former higher sea levels (*e.g.*, stranded shore platforms) have not been included because in this rocky-shore-dominated environment there is coastal mass-wasting, breakage along the fractures of the fracture-dominated lithologies (to release slabs and blocks whose shapes are fracture-controlled) and intense erosion along open shorelines and, as such, there appears to have been continual obliteration of sea level indicators. Any indicators of former higher sea levels in high-level stranded sedimentary deposits, such as high-tidal sand platforms, similarly, have been largely obliterated by sheet wash and slope processes in this tropical setting with high rainfall in the monsoonal months. This is not to say that indicators of former higher sea levels indicators will not be found, but they have been excluded from the list of geoheritage essentials of the Kimberley Coast because they are absent in many localities, or their occurrence is ambiguous in other sites.

Generally, locations for type sections or reference sections for stratigraphic units are listed in the geoheritage essentials of a given area (Brocx & Semeniuk

Table 1

Geoheritage essentials of the Kimberley Coast
i.e., features of geoheritage significance

The extent that a ria coast is developed
Types of rias developed as related to geology
Types of rias developed at different scales
Precambrian geology: geology, stratigraphy, transition of basin to orogen
Geomorphology expressed at the coast
Biogenic coasts (algal and coral reefs)
Tempestites
Barrier sand/gravel deposits
Bar-and-lagoon deposits
Sedimentary sequences
Freshwater seepage and waterfalls
Key hydrodynamic features
Types of cliffs along rias and rocky shore geomorphology
Processes of cliff erosion
Salt weathering
Types of coasts
Diagenetic coasts
Key coastal outcrops
Scenic vistas

2010a), but these tend to be of State-wide importance and are not addressed further as this paper focuses on geoheritage features of International and National significance. Some features of State-wide significance are listed here because they are of National to State-wide importance and are described because at one extreme they can be of National significance and not solely of State-wide significance.

High on the list of features of geoheritage significance (Table 1) is the extent that ria shores are developed along the Kimberley Coast. This is because, while there are other ria coasts elsewhere in Australia and globally (as noted in the review earlier), the ria coast of the Kimberley region is globally an outstanding system in terms of its size and extent, its style of development, and its variability of geomorphic, stratigraphic, hydrological, hydrochemical, and diagenetic features.

Illustrations of coastal forms and coastal features of the Kimberley Coast are shown in Figure 11. Description and assessment of the essential geoheritage components of the Kimberley Coast are presented below.

The ria coast developed along the Kimberley Coast is a megascale feature, assigned to the geoheritage category of modern landscapes and setting (active processes). The Kimberley Coast is the largest ria coast in the World, with an overall length of some 700 km, but unlike other ria coasts developed globally, this coast is cut into resistant Precambrian sandstone, with development of steep cliffs and shoreline bluffs. As such, it is a global classroom, with International significance. The different types of rias developed along the Kimberley Coast, as related to geology, generally are megascale to macroscale features, also assigned to the geoheritage category of modern landscapes and setting (active processes). Within this single region, with (interrelated) geology of Precambrian basin to orogen, the Kimberly Coast presents a globally unique transverse coast where the King Leopold Orogen, comprising multiple lithologies, tight folds, faults, and fractures, all oriented transverse to the coast, crops out along the shore and, additionally, presents an adjoining coastal sector of marine-inundated fluvially-incised terrain. Unlike transverse coasts elsewhere globally (e.g., south-western Ireland), the transverse coast in the Kimberley region is developed on Precambrian folded rock. As described earlier, these tightly folded rocks are the foundation to a (pre-Holocene) ancestral ridge-and-basin geomorphology that, when inundated by the post-glacial marine transgression, has developed coastal landforms reflecting the orientation of the ridge-and-basin geomorphology, *viz.*, ridges, spurs, razorback ridges, oriented narrow inlets, nearly isolated inlets, amongst others. The coastal landscapes themselves are globally unique in terms of their foundation geology, coastal landforms developed, styles of cliffs developed on various lithologies and various structural attitudes, and the large range of scales at which the coastal features are developed.

There are two classic ria forms which, in the literature, have been assigned type locations in disparate areas (*viz.*, transverse rias in the Adriatic Sea and south-western Ireland, and the marine inundated river valleys in north-western Spain). However, in the Kimberley region, both of these ria forms occur adjoin each other, and further occur within the same general oceanographic setting,

with similar coastal processes, within a generally similar tropical climate, and a within a generally similar geology. This is a feature of International significance and, ideally, the Kimberley Coast, comprising coastal forms developed on the Kimberley Basin and King Leopold Orogen *should be viewed as the global type location for ria shores.*

There is another aspect to the types of rias along the Kimberley Coast, and that is the matter of the variety of (river valley) rias developed at different scales. The Kimberly Coast presents a range of ria coast sizes and shapes, some that are fracture-and-fault controlled, varying from large gulfs to small embayments to small ravines, with orientations that reflect the conjugate fault-and-fracture patterns of the region that resulted from the weathering/erosion of the sandstone bedrock, and some that are inundated, rounded hills and undulating terrain that resulted from the weathering/erosion of basaltic bedrock. This aspect of ria shores generally is a megascale to macroscale feature, and is also assigned to the geoheritage category of modern landscapes and setting (active processes). With its expression of marine-inundated rivers, creeks, valley tracts, and ravines of various sizes as ria coasts (since all these marine-inundated valley forms are naturally inter-gradational and form an integrated network), the Kimberley Coast provides a standard of the range of shorelines in terms of shape, sizes, and coastal orientation, that can be assigned to ria coasts and, again, can be viewed as a global classroom. It is a feature of International significance.

The exposure of Precambrian geology along the coast is another important matter in the region. This aspect of the Kimberley Coast is a megascale to macroscale feature, and is assigned to the geoheritage category of geohistorical site. The Kimberley Coast presents well-exposed and extensive coastal cliff outcrops of Precambrian geology, that for over 700 km of general coastal length, and ~ 4000 km of more detailed measured coastal length, exhibit along the shore the sedimentary rocks and facies changes within the Kimberley Basin, volcanic rocks of the Kimberley Basin, as well as the structures and lithology of the King Leopold Orogen, and the geological transition from rocks of the mobile zone (King Leopold Orogen) to those of the Kimberley Basin. This excellent exposure and extent of exposure is a feature of International significance.

The geomorphology expressed at the coast is another important aspect of the region. The landscapes developed at the coast are partly due to the processes of coastal erosion and partly due to inundation of ancestral landforms. As such, fronting the sea, bordering the gulfs, framing the narrow inlets, or forming local islands, there are geomorphic features of sandstone cliffs, cliffs with boulder and scree aprons, plunging basaltic cliffs, bluffs, other types of steep shores, coastally-located mesas, fretted coasts, two-layered and terraced islands and cliffs, and lithologically determined platforms. Edwards (1958) first recognised lithologically determined platforms as coastal features in the Kimberley region along the shores of Yampi Sound in The Buccaneer Archipelago. Many of these geomorphic features are best expressed along extensive coastal tracts involving several to tens of kilometres of coast and should be viewed as an ensemble of coastal forms along a single large coastal tract, rather than as site-specific localities. The various forms of

geomorphic expression along the coast broadly conform to the three sectors of the Kimberley Coast. For example, the coastal tract of sea cliffs between Cape Dussejour and Cape Londonderry, Sector 1, shows an overall straight coast with fracture-controlled mesoscale to microscale ravines and indentations, and lithological control of coastal cliffs and benches, and is a particular type of coast specific to this region. The coast of Collier Bay, Yampi sound, and the Buccaneer Archipelago, Sector 3, shows a highly indented form corresponding to the seaward expression of the ridge-and-basin topography of the King Leopold Orogen. In Sector 3, because of the variable lithology and the structural attitude of the fold limbs, there are various coastal forms developed: rias grading to nearshore islands and rocky reefs and archipelagos; the southern shore of Collier Bay (16° 15' 24" S 124° 0' 20" E) showing a highly indented mesoscale to microscale ria complex dominating the coast; the central north-west trending bay-dissecting peninsula (16° 21' 36" S 123° 56' 33" E) of Talbot Bay showing a crenulate northern coast; the south-western shore of Cone Bay (16° 29' 14" S 123° 30' 8" E) showing an extensive shoreline developed by steeply dipping rocks, oblique shears, and cross-fractures; and Round Hill area, northern Stokes Bay showing the contact between salt flats and rocky shore.

Some of the key geomorphic features along the Kimberley Coast illustrate examples of coastal forms that are particular to the Kimberley region. These include: partially sediment-filled embayment and digitate spur complex around Cape Dussejour; the bar-and-lagoon system between Cape Dussejour and Thurburn Bluff; the narrow v-shaped ravines formed by the bedrock fracture system 10 km south-west of Buckle Head; the two-layered, terraced cliffs formed by the Carson Volcanics and the Warton Sandstone cropping out at the coast in superposition (at Buckle Head, and 5 km NW of Seaplane Bay between Cape Dussejour and Cape Londonderry); Cape Bougainville (a highly dendritic/digitate ria coastal form with bauxite-capped plateau forming the shore and hinterland); the tide-dominated mud delta of the Lawley River; the tide-dominated sand-and-mud delta of the Drysdale River, with its ocean-facing cheniers and spits, the ria coast embayment complex of broad embayments and headland spits of Port Warrender; the peninsula of Pickering Point, the west coast peninsula of Walmesly Bay, and Bigge Island and the adjoining mainland as sites where there are rhomboidal, narrow v-shaped inlet systems formed by erosion of the bedrock fractures; the Mitchell Falls in the Mitchell River area where a riverine waterfall directly contacts with the marine environment at the head of the Mitchell River; the Prince Regent River coast with St Georges Basin and Mount Trafalgar as a large mesa bordering the Prince Regent River coastal complex; the coastal landscape of Prince Frederick Harbour in the Buccaneer Archipelago, featuring a "rock tombolo" attached to a mesa and separating/sheltering a large mangrove-vegetated tidal flat, the Talbot Bay ria system (the linear array of islands and peninsulae of the marine-inundated ridge-and-basin system of the rocks of the King Leopold Orogen).

Generally, the key geomorphic features are megascale to macroscale features, and locally microscale features, and are assigned to the geoheritage category of modern landscapes and setting (active processes) and partly to geohistorical site, the former because it is extant and still

being formed, the latter because some of the landforms are ancestral and manifest pre-Holocene morphology. They are of International to National to State-wide significance from the perspective of geomorphology and from the perspective of scenic vistas (see later).

Algal reefs have been documented elsewhere in the World but they are of different types and in different settings to those of the Kimberley Coast. For instance, in the Bermuda Platform, which is dominantly a coral reef environment, they form "cup reefs" that are isolated algal bioherms with depressed centres and raised rims (James 1983), and in the Caribbean region generally they occur as "algal ridges" associated with coral reefs (Adey 1978; Tucker & Wright 1990; Bosence 1983a). Modern algal ridges and reefs composed of crustose algal frameworks (as distinct from concentrically encrusting rhodolith or rhodoid accumulations; Bosence 1983b, 1983c) have been described from the "coralligène" (in the Mediterranean), at St Croix (Virgin Islands, Caribbean), and the Pacific reefs, and branching frameworks have been described and illustrated from the maerl of the north-east Atlantic (Bosence 1983a). Many of the algal reefs are closely associated as a subfacies of coral reef complexes. The algal reefs of the Kimberley Coast stand distinct as being a fringing algal reef type that inhabits sandstone and basalt rocky shores, forming shore parallel platforms/wedges, and further, these algal reefs are a phylogenetically complex biocoenosis of algae and encrusting and lithophagic invertebrate fauna, rather than an accreted aggregation of crustose algae. Basso *et al.* (2009) document algal rhodoliths on rocky shores of subtropical New Zealand but these are dominantly concentrically encrusting pisoliths and fruticose forms.

The biogenic coasts in the Kimberley region are mesoscale to microscale features, and are assigned to the geoheritage category of modern landscapes and setting (active processes) and partly to geohistorical site, the former because it is extant and still forming, the latter because there are earlier (Holocene) fossil forms buried in the stratigraphy of the deposits. While the algal reefs often form shore-fringing platforms along portions of the Kimberley Coast, their association with a narrow seaward periphery of coral biolithite is particularly important. Because algal reefs are globally uncommon as rocky shore fringing structures, the Kimberley Coast examples are Internationally significant. Bosence (1983c), for instance, illustrates algal reefs along rocky shores, as distinct from coral reef settings, only in few locations globally (*viz.*, along the east coast of temperate climate Canada) and none in the tropical regions of the World.

Similarly, the various types of tempestites in the region, features of mesoscale to microscale size, and assigned to the geoheritage category of modern landscapes and setting (active processes), are of International significance as modern sedimentary models of tropical zone deposits formed in a cyclone-influenced macrotidal coast where corals, shell gravel, reworked beach rock slabs, and local rocky shore derivatives form the source material.

The barrier sand/gravel deposits in the region, especially the lithoclast gravel barriers, are mesoscale to microscale features that are assigned to the geoheritage category of modern landscapes and setting (active processes). Gravel barriers (and gravelly shores) occur

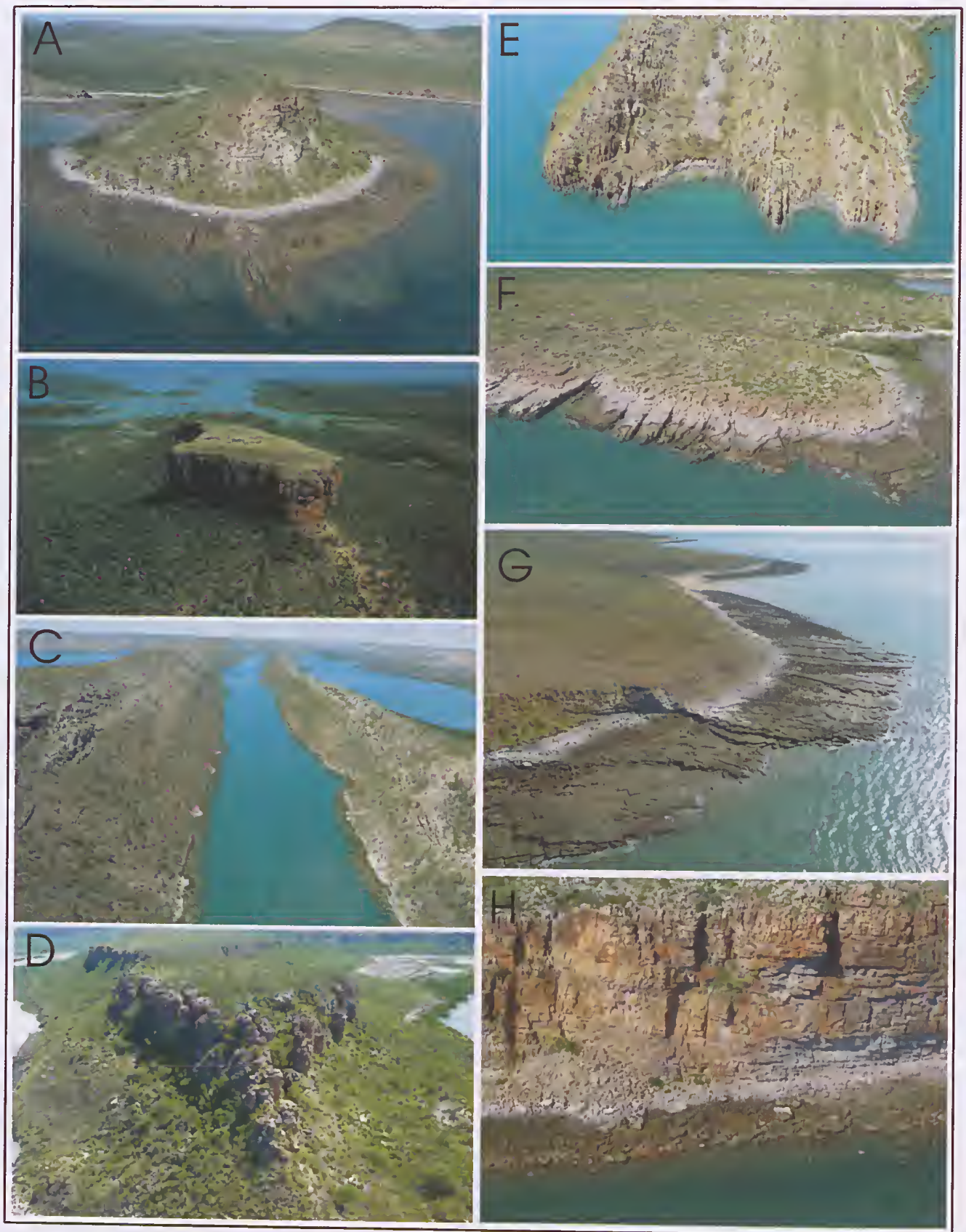


Figure 11. Oblique aerial photographs showing geomorphic features of the Kimberley Coast. A. Typical coastal form in the Kimberley region – an island of eroding jointed sandstone with scree slopes, a tidal/subtidal zone of jointed rocks and veneer of gravel, and a high-tidal to supratidal zone of (bleached) wave-reworked gravel. B. Mt. Trafalgar, a laterite-capped mesa in the Prince Regent River area, showing the nature of landforms that occur at the coast (image courtesy of Yann Arthus-Bertrand). C. Marine inundated ridge-and-basin topography (fold limbs) typical of the Buccaneer Archipelago. D. Spine of sandstone projecting as a peninsula into the sea. E. Crenulate shore formed by vertical sandstone strata. F. Crenulate shore formed by fractures and joints in sandstone. G. Sloping rocky shore formed by low angled inclined strata, with shoreline rubble boulders/cobbles. H. Bouldery shore formed by eroding jointed and bedded sandstone.



Figure 11 (cont.). I. Biogenic shore – algal biolithite fringing a sandstone shore and bouldery shore. J. Biogenic shore – algal biolithite fringing a basalt shore. K. Bar-and-lagoon system, with a sandy barrier. L. Bar-and-lagoon system, with a gravelly barrier. M. Mouth of the Berkley River delta with wave-generated sand ridges. N. Narrow ravine cut into sandstone, and a sandy barrier. O. Tempestite – blocks of sandstone perched on a structural platform of sandstone; cliff of sandstone in far-ground. P. Salt weathering forming a high-tidal pavement on dolerite.

throughout the globe but are associated most commonly with formerly glaciated regions, tectonic coasts where streams deliver gravel to the shore, and wave-dominated rocky shores (Carter 1988; Carter & Orford 1993), e.g., Chesil Bank barring The Fleet (Carr & Blackley 1973), and Haslemere Barrier, both in England. However, the gravel barriers of the Kimberley Coast are specifically formed across narrow ravines cut into Precambrian rock in a tropical macrotidal setting or are reworked scree deposits (where they front the coast) and, as such, are globally uncommon and Internationally significant.

The bar-and-lagoon deposits, especially where the barriers are formed across narrow ravines, are globally uncommon. Essentially, along the Kimberley Coast, the development of bar-and-lagoon systems in a setting of a tropical climate, macrotidal regime, and cyclone influence coast, barriers formed across narrow ravines and embayments cut into Precambrian rock are Internationally significant. These features are mesoscale to microscale, and assigned to the geoheritage category of modern landscapes and setting (active processes).

The ensemble of sedimentary sequences along the Kimberley Coast, located in gulfs, tide-dominated deltas, rias, and other sedimentary settings, range from cyclone-generated tempestites, to mud-dominated systems. Their associated stratigraphic packages, developed by macrotidal and tropical conditions represent a global classroom that shows inter-relationship of morphology, and oceanographic factors such as tide-dominated or wave-dominated prevailing conditions, or cyclone generated conditions, sediment delivery, the dominance of gravel *versus* sand *versus* mud and, as such, are Internationally significant. These sedimentary sequences are megascale to mesoscale features along the Kimberley Coast, and are assigned to the geoheritage category of modern landscapes and setting (active processes).

Freshwater seepages discharging into the high-tidal coastal zone, into scree developed along the interface between basalt and sandstone, and as waterfalls (e.g., the King George River cliffs, Mitchell River, and Crocodile Creek, Buccaneer Archipelago) are widespread throughout the Kimberley Coast. They are mesoscale to microscale features, and are assigned to the geoheritage category of modern landscapes and setting (active processes). The fractured bedrock of the inland Precambrian system functions as a major freshwater aquifer which discharges freshwater into the high-tidal environment, influencing diagenetic and ecological processes (the latter, specifically for mangroves). Commonly, such discharges are along the upper edge of a salt flat at its contact with rocky cliffs, but locally they appear within the salt flat. For mangrove systems (Semeniuk 1983, 1985), in a tropical ria coastal setting, this style and extent of freshwater seepage is a rare hydrological feature and is Internationally significant as a global classroom. Freshwater discharging into scree along the interface between basalt and sandstone are Nationally significant features. Freshwater discharging from rivers, creeks, and rivulets, as waterfalls directly into the sea are Nationally significant features.

The Kimberley Coast also exhibits some key hydrodynamic aspects, such as the "horizontal waterfalls". The "horizontal waterfalls" is a local area (Talbot Bay) within the ria complex of narrow inlets,

parallel inlets, and serial narrow gaps cut into rocky ridges, developed on the King Leopold Orogen, in a macrotidal regime, where there is a lag of tidal water interchange between two parallel inlets and the open ocean developing water level differences of several metres across the gaps. This is an extraordinary tidal hydrodynamic feature because of the configuration of the ria shores and inlets, and is Internationally significant. The "horizontal waterfalls", is a microscale feature, and is assigned to the geoheritage category of modern landscapes and waterscapes (active processes).

While there has been emphasis in this paper on ria form and types of rias along the Kimberley coast, another important aspect of this setting is the types of cliffs along rias and rocky shores. There are, in fact, a variety of cliff types developed along the ria coast and rocky shores, the coastal geomorphology reflecting oceanographic processes, rock type, stratigraphic sequence, geological structure (*viz.*, structural attitude), and the induration, weathered nature and coherence of the bedrock. For instance, exposure of the Precambrian rock sequence to wave, tidal and cyclone activity, and salt weathering in a tropical climate, results in a variety of shore types cut into the rock, and different structurally-oriented rocks that result in plunging shores, rounded plunging shores, terraced shores, razor-back shores, "fretted" shores, "fretted" rock platforms, (vertical) cliff shores, platform-and-cliff shores, bouldery shores (with either rounded boulders, or rock slabs), rocky shores with cobble and pebble veneers (with rounded cobbles/pebbles, or platy cobbles/pebbles), and high-tidal platforms developed by salt-weathering. The range of rocky shores in this region results from the fact that the Kimberley Coast is so laterally extensive, and there is opportunity for a variety of Precambrian rock (of varying lithology and structural attitudes) to be exposed locally to the range of oceanographic processes in a generally similar climatic setting. This is a situation that does not occur elsewhere in Australia. For instance, the Tertiary limestones of the Eucla Basin, exposed in cliffs along the coastal edge of the Nullarbor Plain, though a laterally extensive cliff-line, presents a limited lithology, all in a horizontal structural attitude. Further, the Tertiary limestones are oriented parallel to latitude and front a wave-dominated microtidal ocean of relatively uniform processes which then generates a regionally relatively uniform coast type. Elsewhere the coast of Australia is too heterogeneous lithologically, *i.e.*, without the relatively consistent bedrock, to express the coastal variability of cliff lines that might develop across smaller scale changing oceanographic conditions such as the Kimberley Coast. Examples of the variety of the cliff types along the Kimberley Coast are illustrated in Figure 12. The suite of rocky shore products, illustrating geomorphology and coastal form along the Kimberley Coast, show how coastal form is expressed in laterally variable cliffs and rocky shores and is a Nationally significant classroom for rocky shore geomorphology. The rocky shore geomorphology and features range in size from mesoscale to microscale and leptoscale. They are assigned to the geoheritage category of modern landscapes and setting (active processes).

The processes of cliff erosion along the Kimberley Coast also contribute to the significance of the area. The erosional style is specific to this region because of the

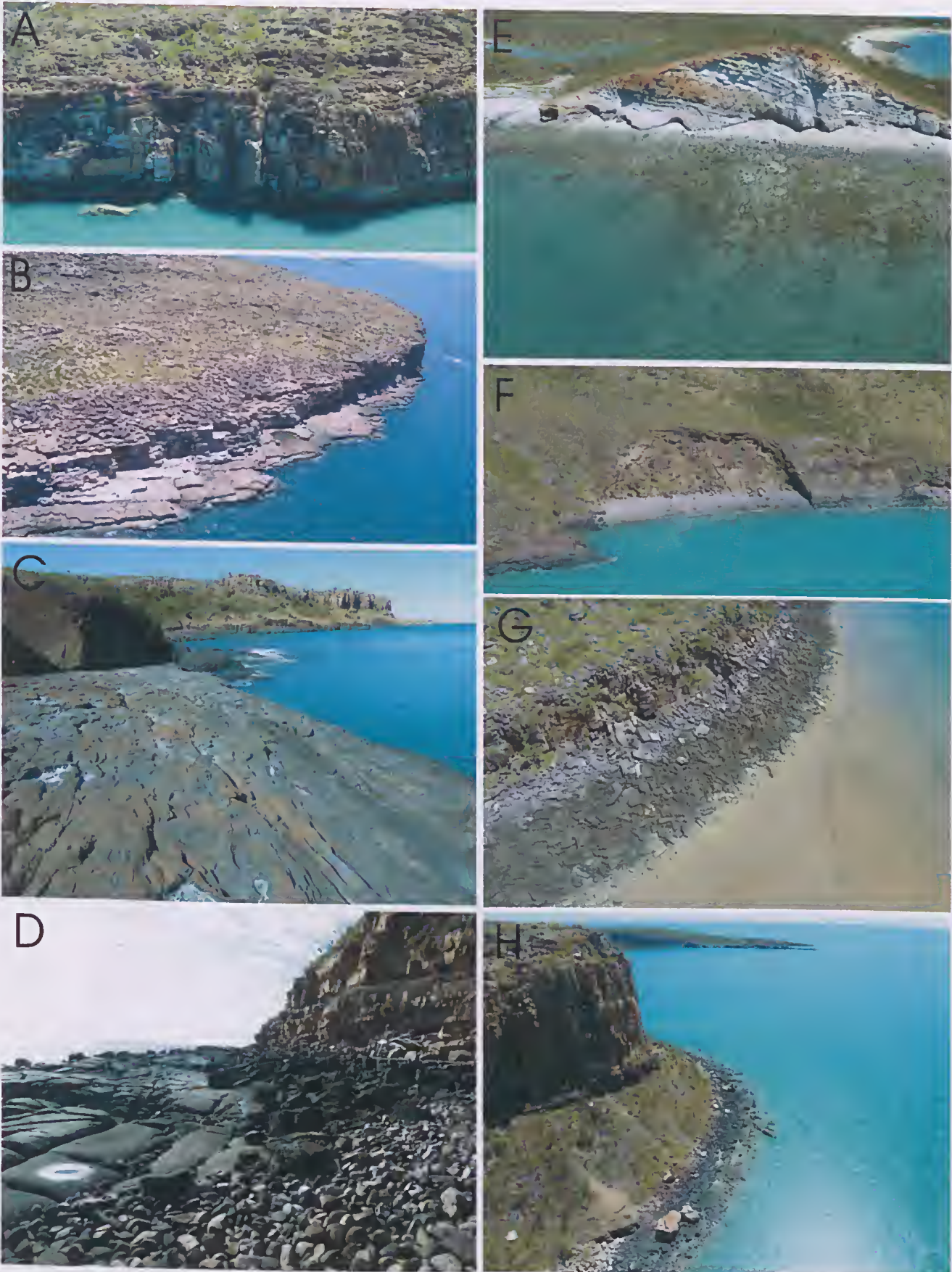


Figure 12. Oblique aerial photographs showing cliffs of the Kimberley Coast. A. Simple sandstone cliff. B. Terraced sandstone rocky shore (terraces controlled by lithology). C. Sandstone overlying basalt with platforms and terrace developed on basalt (foreground) and cliffs in sandstone (far-ground). D. Sandstone overlying jointed basalt; platform developed on basalt, and cliff developed in sandstone; rounded pebbles derived from basalt and sandstone. E. Erosion of sandstone by mass wasting; collapse apron has formed a gravelly shore deposit which descends to the low tide zone. F. Inclined sandstone strata forming plunging shore; erosion by mass wasting forms a pocket beach of sand and gravel. G. Jointed sandstone forming scree being reworked along the shore into boulder slabs. H. Sandstone overlying basalt with cliff in sandstone, and scree slope on basalt; scree develops bouldery shore deposit.

tropical environment, the macrotidal environment, wave action, the lithologies, structures of the lithologies (such as fractures and jointing), and the structural attitude of the rocks. Sandstone, siltstone, and basalt exposed at the shore are actively undergoing erosion by mass wasting, undercutting of cliff faces, joint-block erosion, salt weathering, wave erosion, tidal current erosion, and bioerosion. The suite of processes-and-products is a Nationally significant classroom for erosion processes and erosional products. They are assigned to the geoheritage category of modern landscapes and setting (active processes).

Salt weathering is a component of coastal erosion in this tropical environment, especially along the contact of the salt flats and bedrock cliffs. Salt weathering forms high-tidal pavements at about level of HAT. These pavements can be cut into basalt, dolerite, laterite, sandstone, and steeply dipping rocks. Where cut into steeply dipping rocks, the pavements expose the strata edge-on across the high-tidal flat. Similar pavements produced by salt weathering have been described from the Pilbara Coast (Semeniuk 1996). In the Kimberley region, these high-tidal pavements, indicative of macrotidal environments, range in size from microscale to leptoscale. They are coastal geomorphic features of National geoheritage significance. They are assigned to the geoheritage category of modern landscapes and setting (active processes).

There are a variety of coastal types developed in the Kimberley region, *viz.*, Types 1, 2, 5, 6, 7, 8, 9 and 12, following the classification of Brocx & Semeniuk (2010b) and, as an ensemble of coast types in the region, they comprise a Nationally significant classroom for coastal development and classification, particularly for those that are intergradational. This aspect of the Kimberley Coast generally is a macroscale to mesoscale feature, and is assigned to the geoheritage category of modern landscapes and setting (active processes).

The Kimberley Coast also locally manifests diagenetic coasts, which are generally mesoscale to microscale features. They are assigned to the geoheritage category of modern landscapes and setting (active processes). Such coastal types also occur along the Canning Coast and Pilbara Coast (Semeniuk 1996; 2008), but are not common throughout coastal mainland Australia. The diagenetic coasts (beach rock cemented ramps) along portions of the Kimberley Coast are Nationally significant.

Some of the prominent coastal outcrops along the Kimberley Coast include excellent exposures of sedimentary and volcanic rocks of the Kimberley Basin, and the rocks of the King Leopold Orogen. Examples include the cliffs of Warton Sandstone at Thurburn Bluff, at the entrance and gorge of the King George River, and Cape Rulhieres, outcrop of Carson Volcanics overlain by Warton Sandstone in the Raft Point area, at Buckle Head, and the Osborne Islands, outcrop of Carson Volcanics at Steep Island, cliffs in the King Leopold Sandstone at the Sale River, at Galley Point, and along the shores of Bigge Island, and outcrops of the Yampi Formation along cliffs between Eagle Point and Yule Entrance. Generally, the coastal outcrops are mesoscale to microscale features. They are assigned to the geoheritage category of geohistorical site, and are of National to State-wide significance.

In addition, the Kimberley Coast is well known for its scenic vistas and wilderness appeal. These are megascale to mesoscale features and, depending on location, are of International to National to State-wide importance.

A summary of the geoheritage essentials of the Kimberley Coast within the framework of the Geoheritage tool-kit is provided in Figure 13.

The significance of the geoheritage features along the Kimberley Coast – a discussion

In order to systematically assess the geoheritage significance of this region, the Kimberley Coast has been described geologically and geomorphologically and in terms of its development, as a prelude to applying the Geoheritage tool-kit.

Many aspects of the Kimberley coastal geology and geomorphology are specific to the Kimberley region, and therefore globally unique in their own right, however, there are some geological and geomorphological features that appear to be represented elsewhere globally. Prior to discussing the significance of the geoheritage features along the Kimberley Coast, it should be noted that geoheritage in the foregoing text needs to be viewed from the perspective that this region essentially is a wilderness. Elsewhere, the geological and geomorphological features which are similar are in anthropogenically modified coastal environments dominated by onshore anthropogenic land-uses and hydrochemical contamination, and shoreline harbours, canals, breakwaters, groynes, sediment management, and coastal developments and industry (Fig. 14). For the south-eastern Australian seaboard, for instance, of the three main rias, only the Hawkesbury River estuary remains relatively intact, but its bordering landscape towards its seaward edge is urbanised. Port Jackson is a heavily industrialised and urbanised harbour, and Botany Bay (the seaward portion of the Georges River ria) has an urbanised and industrialised shore and airport runway projecting into the Bay. This pattern of anthropogenic impact is similar for the rias in Spain, Ireland, and Greece. In essence, for many of the ria coasts elsewhere globally there is a strong anthropogenic overprint or influence on the coast and the only features that remain (superficially) unaltered are the geometric form of the ria (as defined by the shoreline) and some coastal vegetation. The gravel barriers developed elsewhere globally manifest a similar pattern, *e.g.*, the barrier of Chesil Bank.

To the already identified importance of the Kimberley Coast, and its unique geological and geomorphological features, is added the unspoiled wilderness setting in which *the ensemble of natural processes are still operating*.

A comparison of the Kimberley Coast in terms of its climate setting, geological features, and extent of ria coastline developed with other coasts worldwide shows that it is globally distinct (Figs 15 and 16). For instance, there are only one other ria coast developed in a tropical climate (Darwin, Australia), and it is much less extensive than the Kimberley Coast. Other ria coasts are developed along shores set in temperate climates, and without the macrotidal and cyclone influence on coastal forms and sedimentation. Rias around the world are generally not

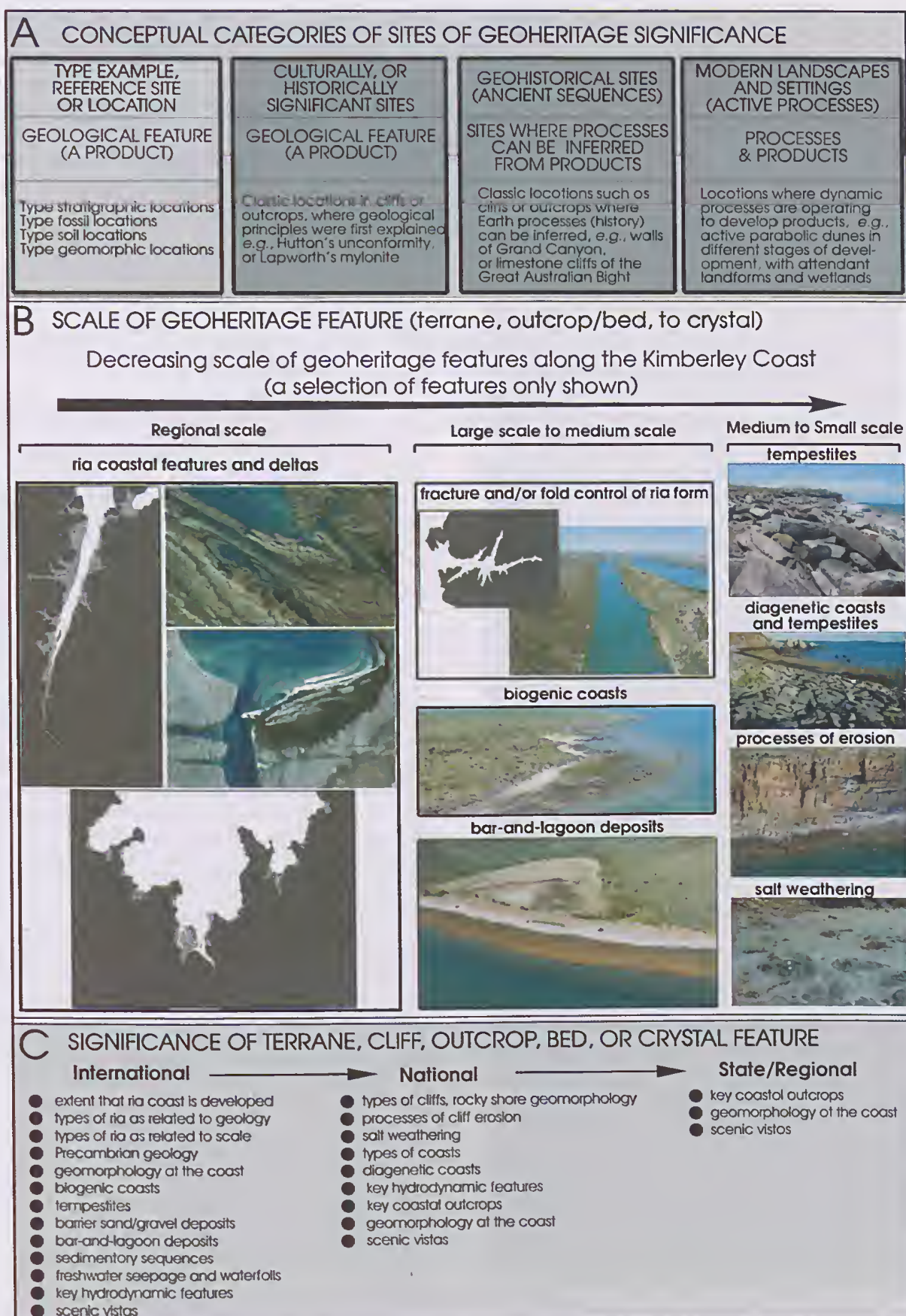


Figure 13. Application of the Geoheritage tool-kit to the Kimberley Coast. In inset A, the categories of geoheritage applicable to this area are highlighted in medium grey (the sites of cultural significance relate mainly to those of Traditional Owners). Only a selection of geoheritage features are illustrated in inset B. The full list of essential geoheritage features of the Kimberley Coast are assigned a level of significance in inset C (see text).

cut into Precambrian rock (Fig. 15). Where a ria system has been cut into Precambrian rock (Darwin), its bedrock is metamorphic rock, unlike the rias of the Kimberley Coast, and it does not present the cliffs, bluffs, and ravines that characterise the Kimberley Coast.

In comparison with the 700 km of Kimberley Coast, the coast of Galicia, Spain, presents a (simplified) length of ~280 km, south-western Ireland presents a length of ~140 km, and the south-eastern Australian rias of Hawkesbury River, Port Jackson (the Parramatta River) and the Georges River involve a combined outer coastal

length of 60 km. Figure 16 shows a range of the well-known ria coasts around the World to contrast their morphology, extent, and size of rias in comparison to the rias of the Kimberley Coast. As a tropical climate ria in terms of size and morphology it is globally unique. By way of contrast, and to emphasise its extensiveness, and global uniqueness, the Kimberley Coast is compared geometrically and in terms of its size to some large fjord suites (Fig. 16). Though not rias, the fjords of northern Siberia, northern Canada, southern Chile and north-western Scotland do show indented coastlines. The Siberian suite does show broad similarity in its indentation geometry in plan, and degree of lateral extensiveness, and the south Chile suite shows fracture-controlled coastal morphology similar to the Kimberley Coast, but all the fjords are set in boreal and arctic climates, and hence have wholly different coastal processes operating.

In the context of being the largest laterally extensive ria coast in the World, the Kimberley Coast presents a range of coastal forms variable in shape, size, and orientation developed on a regionally relatively consistent bedrock template, *viz.*, the rocks of the Kimberley Basin and the seaward expression of the Kimberley Plateau. As such, the ensemble of coasts cut into the rocks of the Kimberley Basin and adjoining King Leopold Orogen present a global example of the range of fracture-and-fault controlled ria coasts that can be developed therein and, ideally, the Kimberley Coast should be viewed as the global "type example" of ria coasts, and a global classroom.

Examples of rocky shore features cut into the Kimberley rocks, and contrasting rock shores cut into the rocks of the Kimberley Basin and those into the King Leopold Orogen, are uncommon in Australia, and, therefore are Nationally significant. Moreover, the rocky shores of the Kimberley Coast are not represented in other indented coasts elsewhere and, therefore the rocky shores, the ensemble of rock types exposed at the shore, and the styles of erosion effected on these rocks in a ria/archipelago setting in the Kimberley region becomes distinct and Internationally significant.

As noted earlier, the Kimberley Coast presents well-exposed and extensive coastal cliff outcrops, for over 700 km of coastal length, of Precambrian geology with exposure of sedimentary rocks and their facies changes, and the intercalated volcanic rocks. This provides a unique opportunity to investigate sedimentary conditions and crustal evolution during the Precambrian times. While there are innumerable undeformed sedimentary basins in the interior of many continents, and outcrop and dissection of these by rivers in many global localities, coasts that intersect sedimentary basins such that they are dissected with cross-basin expression of facies changes along extensive seacliffs are not so common world-wide. The entire western seaboard of North and South America, for instance, is a collision coast of post-Mesozoic age, and thus a folded, faulted, igneous-rock-intruded orogenic belt, without expression of extensive basin dissection along the coast. Similarly, the coasts of the United Kingdom and southern Europe, from Spain to Turkey, are ancient alpine zones (collision zones), with folding, faulting and splintering of sedimentary basins. The Paris Basin in France, Cretaceous to Tertiary in age,

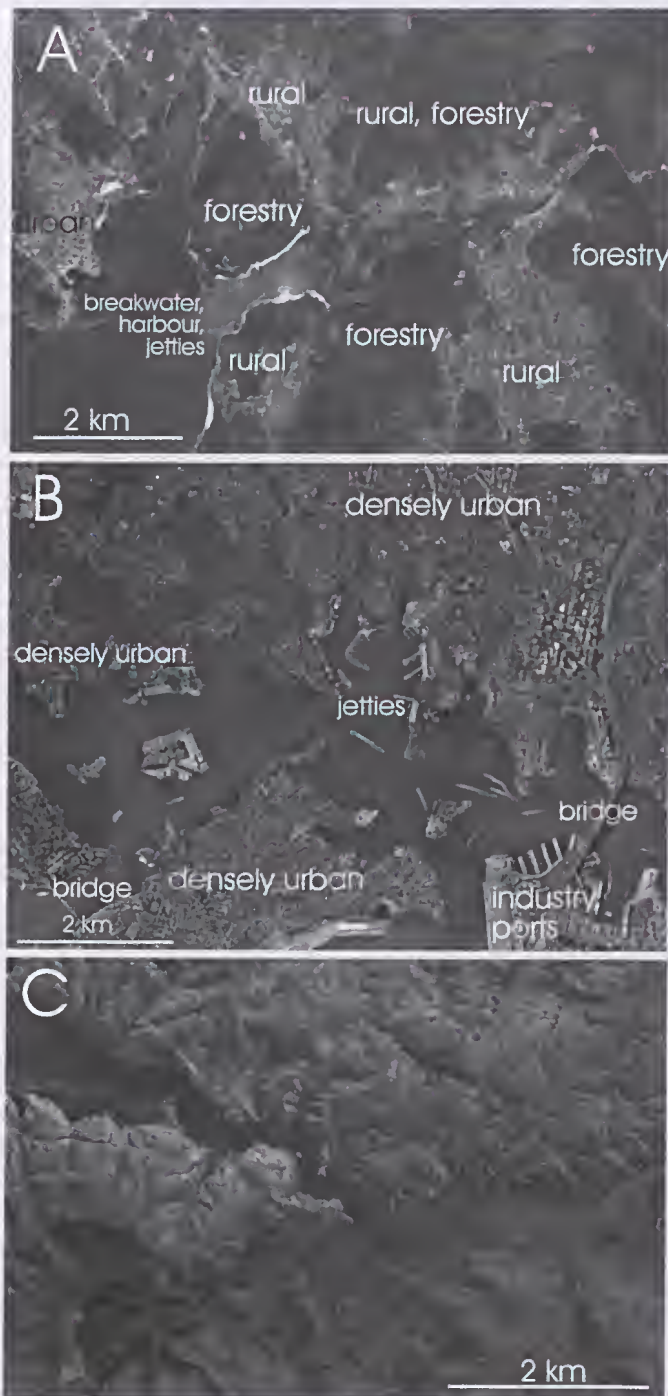


Figure 14. Anthropogenic impacts annotated on ria coasts elsewhere globally, with rural, forestry, urban, industrial, and shoreline impacts, in comparison to the Kimberley Coast. A. Coast of Galicia, Spain (the coast has been outlined in white line). B. Port Jackson, Sydney. C. Kimberley Coast. Images from Google Earth.

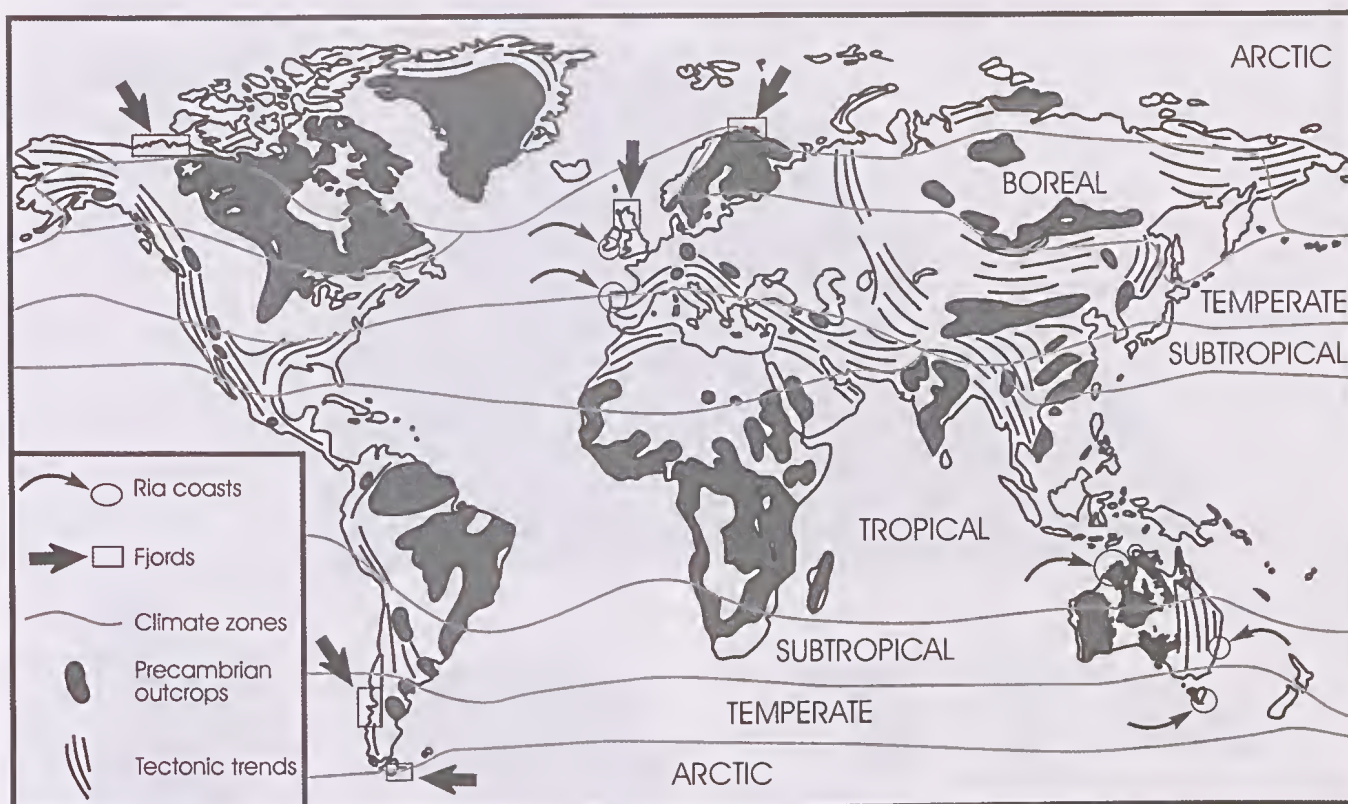


Figure 15. Precambrian rocks globally, their localised occurrence along the coast, and the climate setting of the ria coasts (Precambrian outcrops from Levin 2006; climate boundaries from Trewartha 1968). Few rias are cut into coastal exposures of Precambrian rocks. The examples of rias and fjords in Figure 16 are located as circled and boxed areas, respectively.

though largely a basin occurring inland, does find expression in its cross-basin for 200 km along a coast that dissects and reveals its intra-basinal stratigraphy, but such exposure is mainly the peripheral basin sequences of Cretaceous age (*i.e.*, chalk). The Sydney Basin of south-eastern Australia stands in contrast – it is a large basin exposed for some 500 km of coast, and though there are many intervening sandy stretches and estuaries, there is extensive development of sea cliffs, and with exposure of Permian to Triassic sequences recording marine sedimentation, glacial conditions, coal deposition, submarine lava flows, deltaic sedimentation, and fluvial and lacustrine sedimentation (Packham 1969). The sea cliffs cut into the rocks of the Sydney Basin thus expose sequences that illustrate basin evolution, sedimentary history, facies changes, and specific stratigraphic sequences and relationships across a widespread area and is a geological feature of global significance. The limestones of the Eucla Basin, mentioned earlier, cut by the cliffs along the edge of the Nullarbor Plain between Western Australia and South Australia, is of a similar nature, though restricted to sedimentary sequences of Tertiary age. Some 1000 km of the Eucla Basin is exposed along the shore (though not all of the rocks of the basin are exposed along seacliffs) to show sedimentary sequences and lateral facies changes. It also is a world-class exposure of the interior of a sedimentary basin.

In this context, the Kimberley Coast dissects a laterally extensive sedimentary basin whose rocks are well exposed almost continuously along its outer shores and the inner ria shores. Simply, as an extensively exposed sedimentary basin, the Kimberley Basin already qualifies

as a region of global importance in the same manner that the Sydney Basin and Eucla Basin are significant, however, it has the added importance of *being a basin of Precambrian age* and, as such, the rocks exposed along its shores illustrate sedimentary history, facies changes, and volcanism in its content, and exposure of a Precambrian basin unparalleled in the World.

Excellent coastal exposures also occur in the megascale to microscale structures, and the lithologies of the King Leopold Orogen cropping out along the southern part of the Kimberley Coast. The folded, faulted, and metamorphosed rocks and the geological transition from rocks of the mobile zone (King Leopold Orogen) to those of the Kimberley Basin are well-exposed, and provide a world-class example of this type of geology.

The combination of bedrock types and structures, waves and tides and tropical climate and cyclones result in a suite of products that create an Internationally to Nationally significant classroom for rocky shore geomorphology. For example, the algal reefs forming shore-fringing platforms along portions of the Kimberly Coast appear to be a feature of a tropical coast that is dominated by rocky shores. The various tempestites, the barriers of gravel, especially the lithoclast gravel barriers, and the bar-and-lagoon deposits, are the result of coastal processes acting on various source materials such as coral gravel, lithoclast gravel, and beach rock slabs in a cyclone-influenced area within a fractured rock system that has produced specific coastal geometric and scalar forms. The variety of cliff types and rocky shores along the ria coast, reflect oceanographic processes, rock type, stratigraphic sequence, and geological structure.

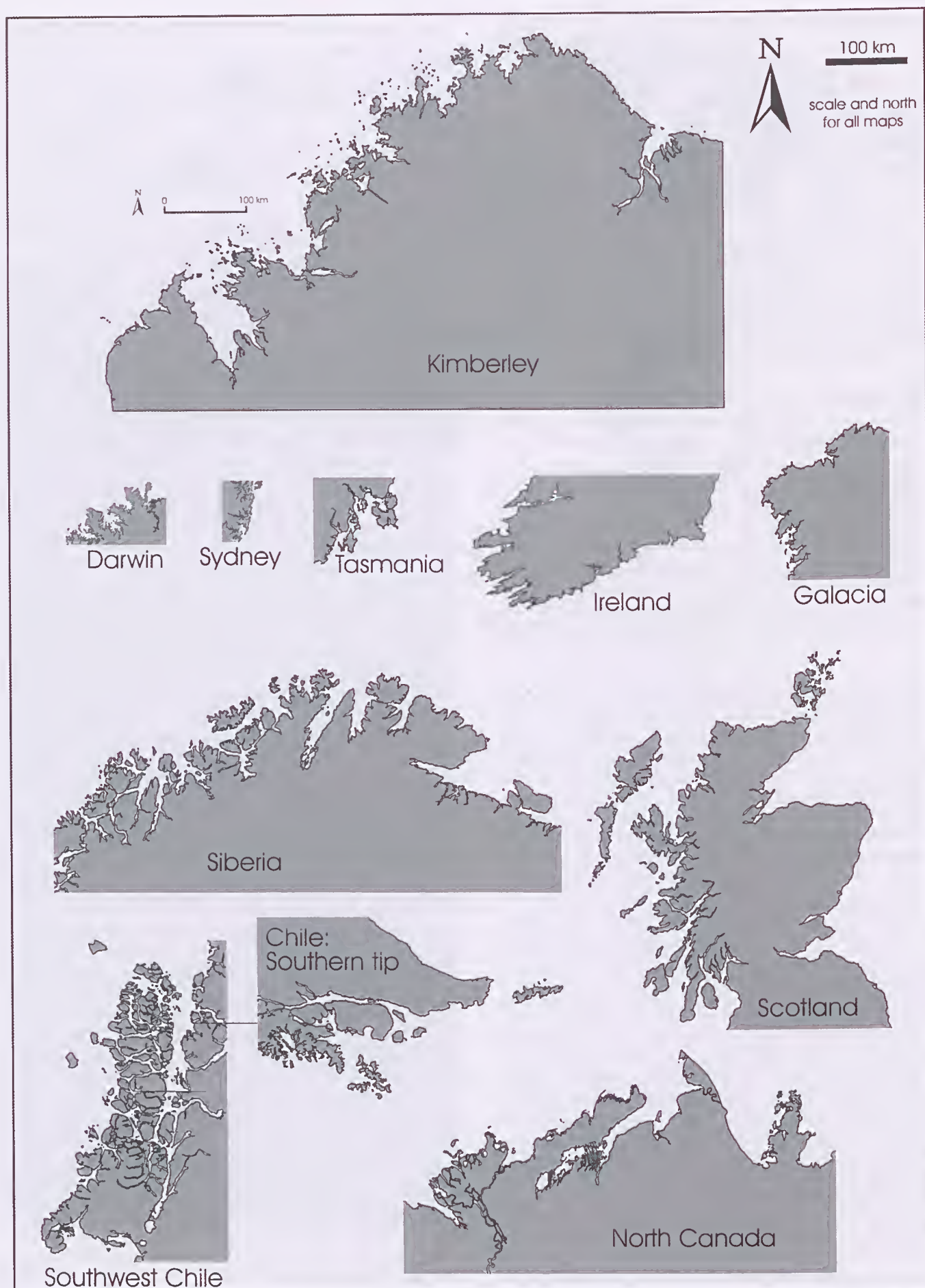


Figure 16. Comparison of the size, extent, and plan-geometry of some rias and fjords of the world in comparison to the Kimberley Coast.

Most Western Australian examples of high-tidal pavements formed by salt weathering signal macrotidal environments and processes operating at levels of the highest tides where the salinity of groundwater and soil water in a tropical environment are at their most elevated (Semeniuk 1996). In the Kimberley region this type of coastal weathering is superimposed on a variety of rock types and, as noted above, this enhances their geoheritage significance.

A generally overlooked aspect of geoheritage is hydrology. This is a subdiscipline within geology and in many respects drives diagenesis and weathering of rocks. In its own right hydrology is a fundamental part of the Earth processes and products. When frozen, water as ice is studied as an important part of geology in the field of glaciology, but while still liquid it is often ignored as a geological phenomenon (the exception being its hydrochemical and physical role in diagenesis and pedogenesis). The largest focus on water in the geological sciences is on its role as a medium that transfers energy as waves and currents and that can transport sediment or erode substrates. Previously, Brocx & Semeniuk (2007) have emphasised that hydrology as part of geology should also be captured as part of geoheritage. For the Kimberley region, along the coast, hydrology is an important part of the natural environment of extant processes because the fractured bedrock in the region acts as a major freshwater aquifer and discharges freshwater into the high-tidal environment, influencing ecological processes (specifically mangroves), cementation, and other coastal processes. This means of hinterland-to-coastal hydrological exchange is essential for some of the assemblages of mangroves along the Kimberley Coast and, in addition, results in an array of diagenetic and sedimentological products, and ecological products. Fractured sandstone overlying relatively less permeable weathered basalt results in seepage of freshwater along the basalt/sandstone interface and in the development of habitats for Kimberley rainforests (McKenzie *et al.* 1991), particularly where the interface is covered in scree.

The sediments of the Kimberley Coast are important features of the region, but need to be viewed as a regional ensemble of sediment packages. To date, sedimentologists and coastal scientists tend to view the coast in isolated segments and, as such, study in detail the coastal setting, sedimentology and stratigraphy of these isolated packages. In Western Australia, for example, Logan and colleagues studied the Shark Bay sedimentary environments (Logan *et al.* 1970, 1974) without a regional context of the larger sedimentary basin setting of the Carnarvon Basin so that adjoining sedimentary packages were not related to Shark Bay. Similarly, Johnson (1982) studied the Gascoyne River delta in isolation without relating it to the neighbouring Shark Bay sedimentary system. This is not to discredit the effort of these researchers in describing the coastal processes and products at the site-specific areas, but the inter-relationships of the sedimentary packages generally are not synthesised into a regional framework and, in the case of Shark Bay and the Gascoyne River delta, into the context of a sedimentologically-active and tectonically-active Carnarvon Basin, an aspect that is important if assessing the geoheritage significance of sedimentary systems. An exception to this case-by-case, cove-by-cove,

and embayment-by-embayment approach is Fairbridge (1992) who, in a review of the literature, provided a continent-wide view of the coastal sediments of North America showing the inter-relationships of the sedimentary cells, sediment pathways, and the inter-relationships of sedimentary systems along the east and west seabords of North America. This approach showed the inter-relatedness of sedimentary systems and could form the basis of identifying larger-scale features of geoheritage significance. Rather than view each gulf and embayment and local cove as a separate sedimentary system, the entire Kimberley Coast can be viewed as an interrelated sedimentary system wherein the various sedimentary packages are reflecting, at the largest scale, variability in bedrock geology, drainage basin configurations, drainage basin size and its setting in a given rainfall regime, coastal form, site-specific sedimentary systems, sediment supply, and coastal processes. Thus the sedimentary sequences along the Kimberley Coast located in gulfs, in tide-dominated deltas, rias, and sedimentary suites, ranging from cyclone-generated tempestites, to coastal sedimentary suites and mud-dominated sediment systems, and their associated stratigraphic packages developed by macrotidal and tropical conditions, should be viewed as a heterogeneous and patchy response to the regional abiotic and biotic processes acting on the regional geological template. In other words, there is interplay between coastal processes, coastal forms (dictated by geology, structure and drainage basins), sediment supply (dictated by drainage basins and bedrock) and sediment type. Viewed in this manner, the sedimentary packages of the Kimberley Coast as an integrated system are globally unique, and present a unified model that shows the inter-relationship of morphology, and oceanographic factors such as tide-dominated, wave-dominated, or cyclone-generated conditions, sediment delivery, the dominance of gravel *versus* sand *versus* mud, and other factors as outlined above.

Given the descriptions above of all the Geoheritage essentials, the unique and important nature of the Kimberley Coast should be viewed as an International and/or National conservation system (Step 6 of the Geoheritage tool-kit), essentially a mega-geopark, within which there are many features of International significance, thus integrating the many smaller-scale features of geology and geomorphology into a single geoconservation unit, *i.e.*, the geopark. In the UNESCO definition of a geopark, the Kimberley Coast qualifies in containing numerous “*geological heritage sites of special scientific importance*”. The various components of the geoheritage of the area should be viewed not in isolation, as type locations, or “best example of a given feature”, but as the integrated system of geological products and as integrated systems of processes-and-products. Coastal evolution and form, its associated sedimentary evolution, and the exposure of Precambrian stratigraphy are examples of these principles. Algal reef, diagenetic coasts, and freshwater seepage are further examples.

As a remote wilderness area, that has not previously described for assessing sites of Geoheritage significance, the Geoheritage tool-kit has been applied to identify and rank features of geoheritage significance using an inventory-based approach that assigns a level of

significance to geological features regardless of their scale and within a framework of the broadest possible definition of the Science of Geology. It is not possible to include all geological features of microscale and leptoscale at this stage and as more geological studies of this region are undertaken, it is assumed that this initial inventory will be revised, updated, and supplemented with information that will lead to the appropriate conservation category, and management.

The Kimberley Coast can in fact be used as a case study for inventory based assessment of Geoheritage significance globally. This is because it contains a wide variety of geological and geomorphological features, varying in significance from International to State-wide, and this study demonstrates how the Geoheritage tool-kit can be applied to geological sites, or regions, to determine geoheritage values for conservation and management. However, it should be appreciated that the Kimberley Coast has a large number of geological and coastal geomorphological features that are of International significance in a tropical wilderness setting and it is unlikely that there are many other Regions elsewhere with the number and range and scope of sites of geoheritage significance found on the Kimberley Coast.

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Geological Setting, Marine Geomorphology, Sediments and Oceanic Shoals Growth History of the Kimberley Region

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Abstract

The offshore sedimentary basins of the Kimberley region are becoming established as a major hydrocarbon province, but the region is also known for its marine wilderness values. Its position close to a plate boundary is reflected in significant rates of continental margin subsidence. In addition to the "normal" continental margin geomorphic units of shelf, slope and rise the offshore Kimberley region has well developed plateaux (e.g. Scott Plateau), terraces (e.g. Rowley Terrace), and banks (e.g. Sahul rise, Sahul bank) which interrupt the otherwise gentle seaward slopes present, and provide foundations for the offshore reefs, including the Sahul shoals, Ashmore, Seringapatam, and Scott Reef and the Rowley Shoals. The continental shelf is a vast low gradient ramp with sandy bioclastic sediments reflecting both the modern biota and a history of past sea level and oceanographic changes, so that sediments are a mixture of modern bioclasts, particles stranded by sea level rise, and precipitated carbonate grains (ooids and peloids) which were dominant prior to Leeuwin Current onset some 12,000 years ago. Whilst little is known about the nearshore fringing reefs, in areas of macro-tides and significant sediment input, the morphology, internal architecture and growth history of reefs and shoals of the Oceanic Shoals Bioregion indicates that these are long-lived features which have survived despite relatively high rates of continental margin subsidence and oscillating sea levels of the Pleistocene glaciations. However, drowning by sea level rise was the fate of some of the reefs and shoals of the Sahul Shelf, situated at the leading edge of the downturning Australian Plate, in contrast to continuing reef growth at Scott Reef and the Rowley Shoals to the south. In the morphological series provided by the three Rowley Shoals, differential subsidence is the primary control on rates of lagoon infill controlling platform morphology. This study demonstrates the resilience of reefs on the subsiding margin whilst linking reef morphology to the relative amount of pre-Holocene subsidence.

Keywords: geomorphology, Kimberley, continental shelf, sediments, Oceanic Shoals Bioregion, coral reefs, sea levels, growth history, subsidence

Introduction

The remote Kimberley Region in north Western Australia has a deeply embayed tropical macrotidal coast fringing an onshore complex of Proterozoic rocks known as the Kimberley Basin, which is bordered by Phanerozoic sedimentary basins (Fig. 1). Whilst the marine realm is essentially a wilderness region there are significant discoveries of hydrocarbons offshore, and this is driving the development of the petroleum industry with several fields discovered and offshore gas developments foreshadowed. The offshore and onshore infrastructure requirements of these activities will have impacts in both terrestrial and marine environments, and this new phase of activities has already commenced. Recently we have seen a major oil spill at the Montara wellsite, an ongoing land use and heritage dispute over the proposed gas hub site at James Price Point, and newly declared marine and terrestrial parks in the region.

The purpose of this paper is to provide some of the geological and geomorphological framework which is relevant to the region and its biodiversity, with particular

reference to the remarkable offshore reef systems which characterise the outer parts of the continental shelf, close to some of the hydrocarbon discoveries.

The continental shelf and margin are in the domain of the Indian South Equatorial Current. It is situated in a tropical marine realm, with warm temperatures between 26–28 °C, and lower salinity (34.5 to 35.7) that characterises the waters in the proximity of the Indonesian Throughflow. Offshore areas have clear waters due to low nutrient levels and no continental sediment input, because of distance from the coast, providing an ideal environment for the development of coral reef communities. The proximity to the Indonesian Throughflow has been shown to increase the importance of both Pacific and Asian reef species southward, and the Leeuwin Current, which flows southwards against the prevailing equatorward winds, is an important control on larval delivery, whilst suppressing upwelling along its path (Fang & Morrow 2003). The North West Shelf is tidally dominated, with coastal mean spring range increasing from 1.7 m at Exmouth to 9.2 m in King Sound (Harris *et al.* 1991). Both Scott Reef and Rowley Shoals have semi-diurnal tides with a tidal range of 4.1 and 4.5 m respectively (National Tidal Center 2009a, b; meso-

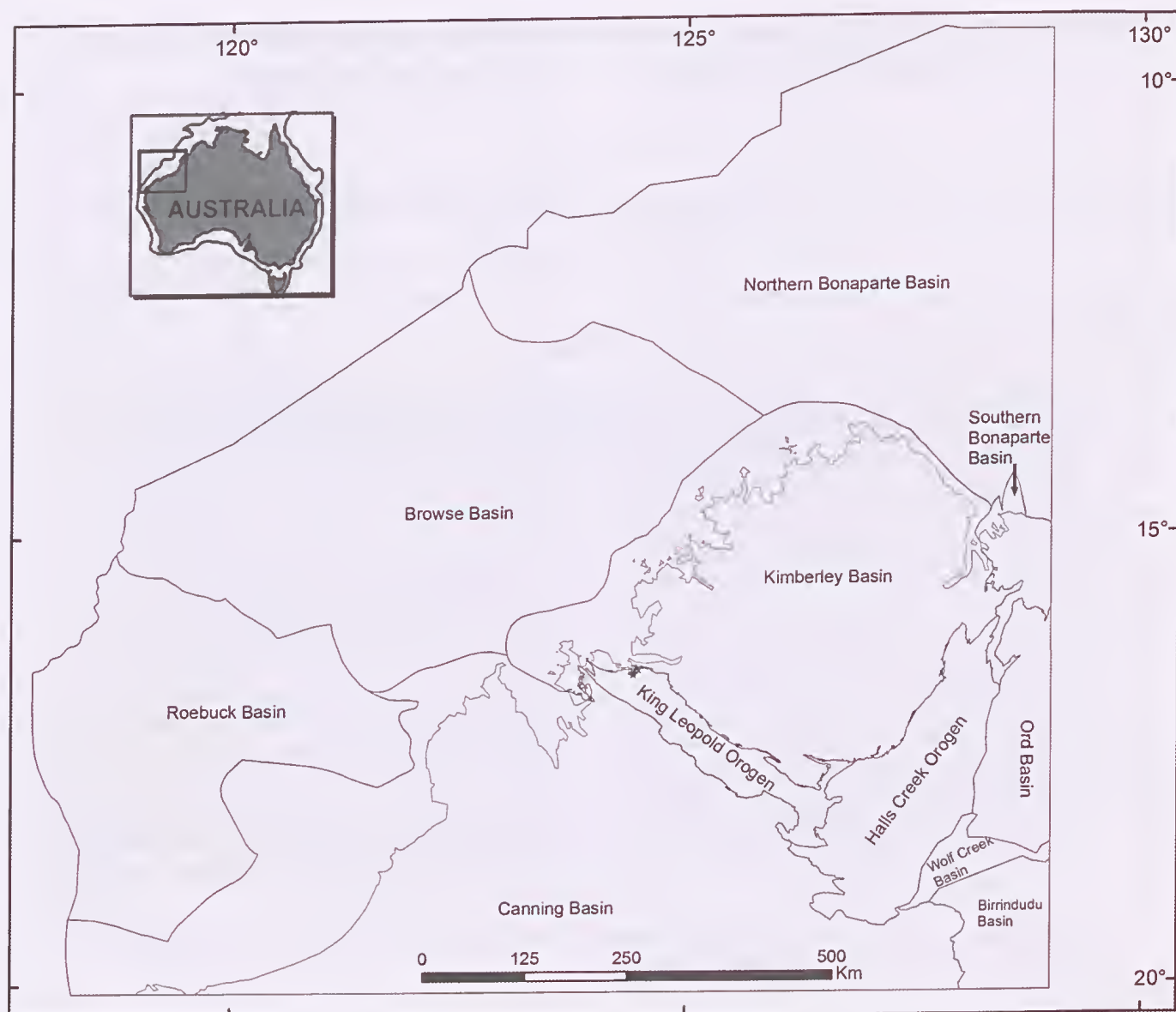


Figure 1. Onshore geological elements and sedimentary basins of the Kimberley region

high tidal range, *sensu* Hayes 1975). The region lies in the monsoonal belt with prevailing westerly or northwesterly rain-bearing winds from November–March, and dry southeasterly or easterly trade winds from May to September. The region is cyclone-influenced (average 3 per year, Lough 1998) and has southwest prevailing swell.

Methods

Background information on geology, geomorphology and bioregions was acquired from various sources referred to in the text. Shelf sediment mapping (by James, Bone and Collins) is summarised from James *et al.*, (2004). Offshore field surveys were carried out using the CSIRO research vessel RV Franklin during Voyage FRO5/00, for collection of seafloor samples, bathymetric profiles, and shallow seismic data. Both shipboard and small vessel seismic surveys were conducted using an ORE Model 581 3A Acoustic Source (Boomer), driven by a Geopulse 5420A power supply. A Benthos multi-element streamer

was used for small vessel work and a Teledyne 4 channel streamer was used for Franklin work. The seismic acquisition system used was a Geoacoustics SE88 1 Sonar Enhancement System, and a Garmin GPS unit supplied GPS data to the acquisition system on the small vessel. Franklin DGPS data were supplied and processed by Navipac software for onboard seismic acquisition.

Oceanographic data were acquired using CTD and bathymetric data by PDR (Precision Depth Recorder). Geological sampling was by Epibenthic Sled and Gravity Corer. No core data was obtained for the Rowley Shoals, and limited core was available for Scott Reef. Cores were logged and dated using U series TIMS methods (University of Queensland, Centre for Microscopy and Microanalysis) by the dating techniques of Zhao *et al.* (2001) and Yu *et al.* (2006). Rock types were characterised using the Expanded Dunham Classification (Embry & Clovan 1971) for depositional textures, and the characterisation of main biological facies followed the scheme of Montaggioni (2005). Sediment data for the southern Kimberley Region and adjacent Canning

Bioregion are discussed, the latter included for comparative purposes. The data also applies to the contiguous Northwest Shelf (NWS).

Geological Setting

The onshore geology is dominated by the Kimberley Basin (Fig. 1) which consists of Proterozoic rocks

(Speewah, Kimberley and Bastion Groups) which consist of sandstones, siltstones and volcanics, with stromatolitic dolomites (GSWA 1990). Locally extensive sheetlike bodies (sills) of the Hart Dolerite are conspicuous, and in the southern part of the basin glaciogenic rocks are common. Narrow belts of deformed rocks (the King Leopold Orogen to the southwest and the Halls Creek Orogen to the southeast) demarcate the margins of the

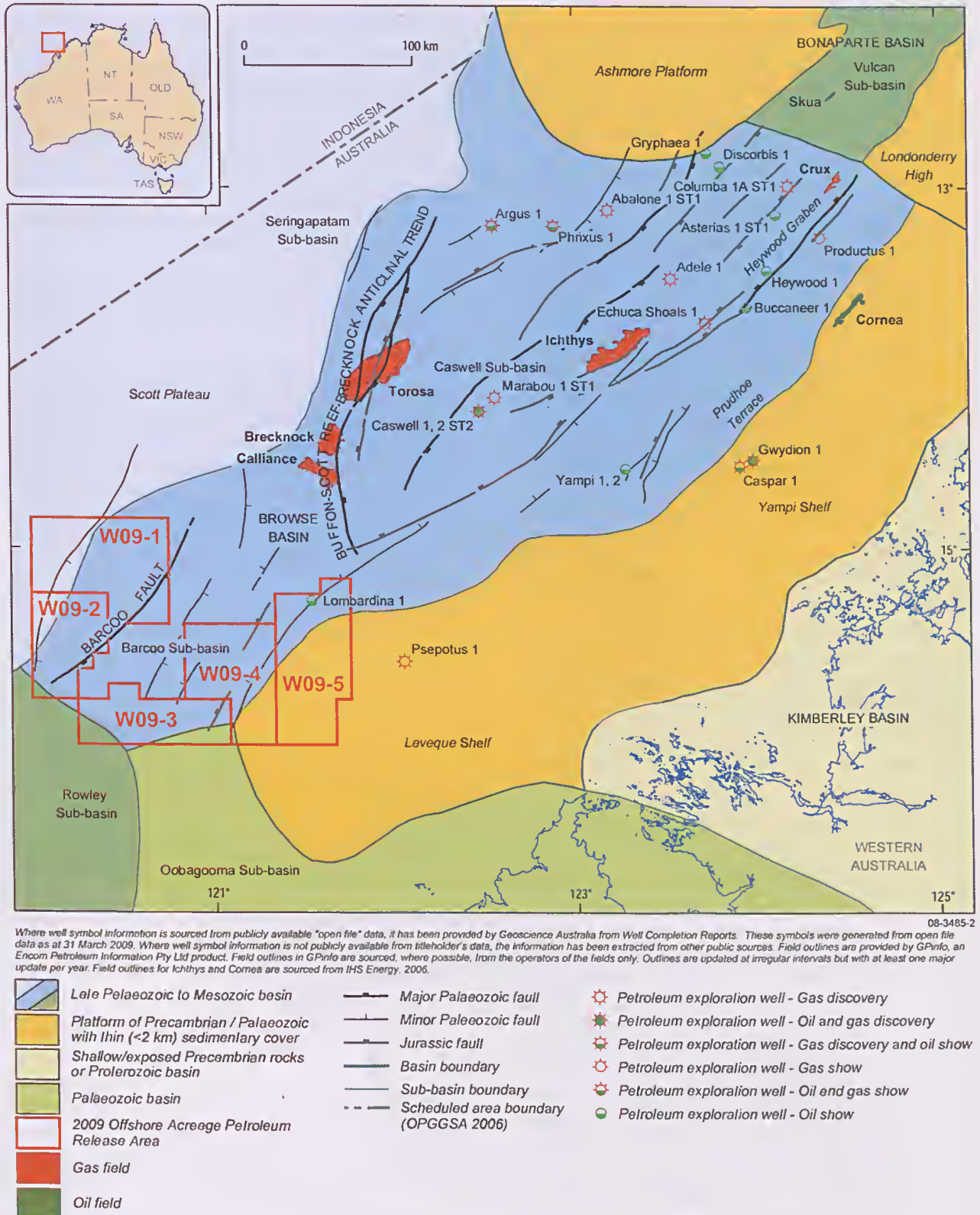


Figure 2. Significant hydrocarbon discoveries and fields of the Kimberley region. (Department of Mines and Petroleum).

Kimberley Basin (Fig. 1). These mobile belts give way to extensive onshore Phanerozoic sedimentary basins (the Canning and Ord basins, respectively). The Canning Basin is known worldwide for its exposures of Devonian reef complexes (see Playford *et al.* 2009).

Offshore the Bonaparte Basin in the northeast and the Browse Basin to the northwest contain thick sedimentary sequences which host the hydrocarbon discoveries and fields which are in various stages of development (Figs 1, 2). The geological history of the offshore regions has been controlled by breakup of the Gondwana supercontinent and earlier events spanning some 400 Ma (million years), and 3 stages of evolution are recognised: the pre-rift, syn-rift and post-rift stages (Struckmeyer *et al.* 1998; Kopsen 2002). During the pre-rift stage the region was part of an extensive basin connected to a northern seaway (Triassic-Lower Jurassic time; 250–180 Ma approx.) and marine shales to fluvio-deltaic sediments were deposited. The breakup or syn-rift events that followed increased marine influences and deposited organic-rich shales (the source rocks for most of the hydrocarbons) following which the rift was progressively infilled by shallow water sands and fluvio-deltaic sediments until rifting ceased in the Early Cretaceous time (120 Ma approx.). Thermal subsidence and reduced tectonic activity marked the subsequent post-rift stage during which mainly carbonate ramp deposits accumulated and this stage continued through to the present time, providing a package of limestones over 2000 m thick; this provided both a seal for deeper hydrocarbon reservoirs and the

necessary overburden to allow maturation of the hydrocarbons. Early stages of collision of the Australian plate with the Eurasian plate to the north (Miocene time; last 28 Ma approx) caused crustal flexure and generated deep troughs and intervening structural highs (Sahul, Ashmore and Scott Platforms). These in turn provided suitable foundations for many of the offshore coral reefs of the region.

The offshore Kimberley region, particularly the Browse Basin (Fig. 2) has proven hydrocarbon reserves in the Calliance, Brecknock, Torosa (near the Scott Plateau), Ichthys and Cornea fields, with additional reserves in the Bonaparte Basin to the north, and several other discoveries undergoing evaluation and/or further exploration. Most of these will require onshore infrastructure, pipelines and marine servicing, although offshore development remains an option for the future. Also shown is the 2009 exploration acreage release area close to the Rowley Sub-basin to the south, and further exploration successes are anticipated.

The Ichthys field is now scheduled for development in the Northern Territory, a plan which may also apply for some (but perhaps not all) of the Bonaparte Basin fields.

Geomorphology and Sediments

Australia's margin in the EEZ has been recently mapped (Heap & Harris 2008) and a summary of this work for the study area (Fig. 3; Table 1) illustrates that,

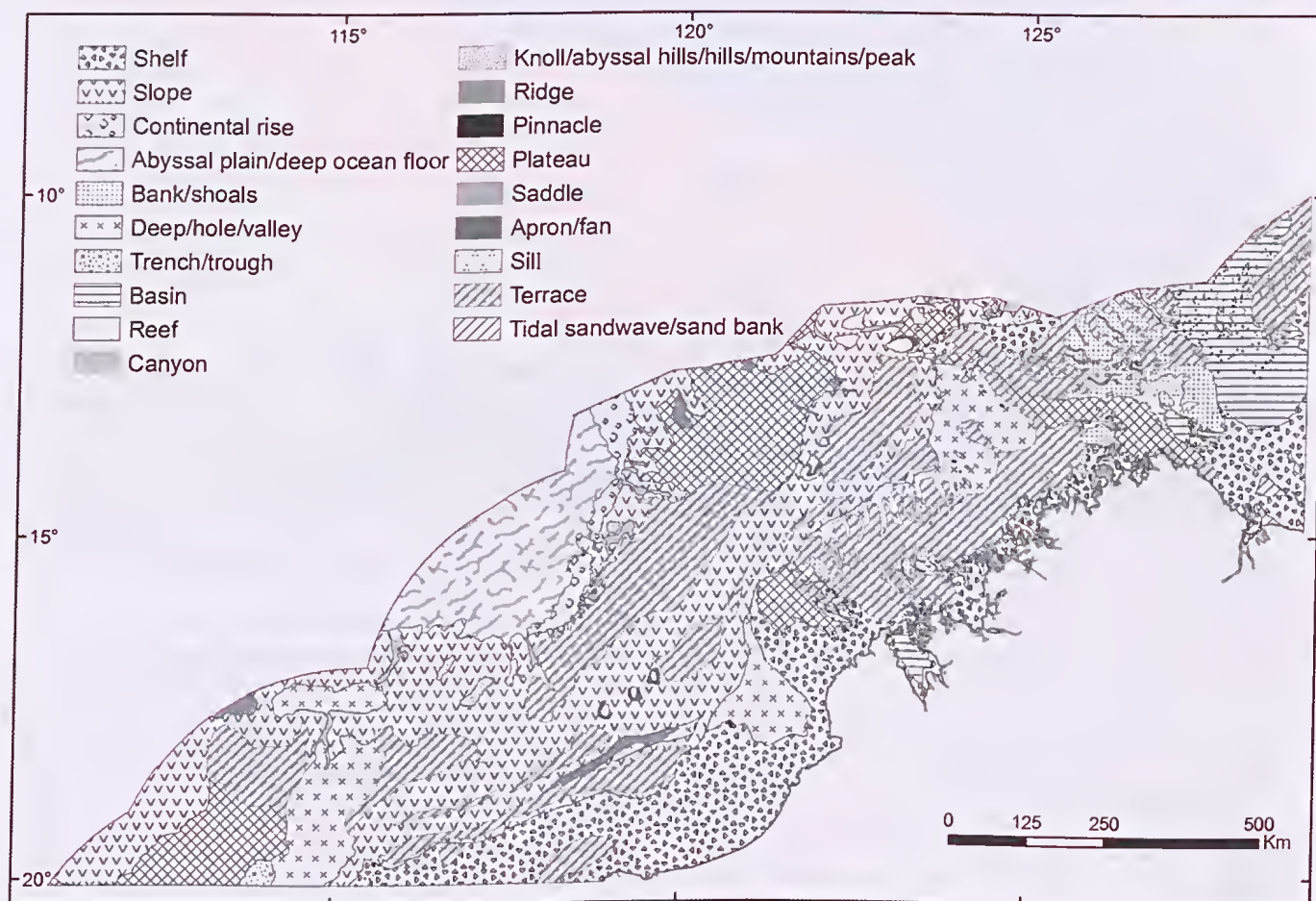


Figure 3. Geomorphology of the offshore Kimberley region, after Heap & Harris 2008.

Table 1

Summary of Geomorphic subdivisions compared with IMCRA meso-scale bioregions for the study area. Summarised from Heap and Harris (2008) and IMCRA data. The corresponding mesoscale bioregions are OSS and NWS (Oceanic Shoals, North West Shelf; shelf to slope) and KIM and BON (Kimberley and Bonaparte, coastal and nearshore shelf).

Geomorphic Provinces	Description
Shelf Zone	Adjacent to a continent (or around an island) and extending from the low water line to a depth at which there is usually a marked increase of slope towards oceanic depths.
Slope	Slope seaward from the shelf edge to the upper edge of a continental rise or the point where there is a general reduction in slope.
Rise	Gentle slope rising from the oceanic depths towards the foot of a continental slope.
Abyssal Plain/ Deep Ocean Floor	Extensive, flat, gently sloping or nearly level region at abyssal depths.
Bank	Elevation over which the depth of water is relatively shallow but normally sufficient for safe surface navigation.
Shoal	Offshore hazard to surface navigation that is composed of unconsolidated material.
Reef	Rock lying at or near the sea surface that may constitute a hazard to surface navigation.
Terrace	Relatively flat horizontal or gently inclined surface, sometimes long and narrow, which is bounded by a steeper ascending slope on one side and by a steeper descending slope on the opposite side.
Plateau	Flat or nearly flat area of considerable extent, dropping off abruptly on one or more sides.

in addition to the “normal” continental margin geomorphic units of shelf, slope and rise the offshore Kimberley region has well developed plateaux (e.g. Scott Plateau), terraces (e.g. Rowley Terrace), and banks (e.g. Sahul rise, Sahul bank) which interrupt the otherwise gentle seaward slopes present. These features also provide foundations for the offshore reefs, including the Sahul shoals, Ashmore, Seringapatam, and Scott Reef and the Rowley Shoals. Many of these reefs are likely to be long-established features which initially grew along a now-drowned former Miocene shoreline (Collins 2010).

Following pioneering work on the sediments of the region by Jones (1973) a detailed sedimentological survey was completed by James *et al.* (2004) for the southern part of the Kimberley region and North West Shelf (NWS), and much of the information is broadly applicable to the Kimberley so is summarised here (from James *et al.* 2004). The continental margin is a relatively simple seaward incline or ramp which can be partitioned on the basis of hydrodynamics and bathymetry into inner ramp (<50 mwd (mean water depth) -fair-weather wave base), mid-ramp (50–120 mwd-storm wave base) and outer ramp (>120 mwd). An important feature is a terrace, the base of which is at 125 mwd, occurring along the length of the shelf and backed by a 30 m high escarpment; interpreted to be the Marine Isotope Stage 3 lowstand shoreline which formed about 20,000 years BP (before present) (James *et al.* 2004).

Modern Sedimentation: Ramp Surficial Sediment

Overall the surface sediments are sand and coarser dominated (Fig. 4), ≈ 90% carbonate, and contain abundant relict material with authigenic phosphate and glauconite components. Deep-water sediments are planktic muddy sands while the shelf materials are skeletal, peloidal and oolitic. The coarse fraction (> 2 mm) is entirely skeletal, consisting of molluscs, benthic foraminifera, bryozoans, echinoids, calcareous algae and

corals. *Amphistegina* and miliolids are the dominant benthic foraminifera, while most of the molluscs are bivalves. The mud-sized fraction is composed of skeletal debris, silicate clays, quartz and micrometre-sized aragonite needles. Terrigenous and high-magnesium calcite (HMC) components are highest near the shoreline, whereas aragonite needles are most abundant on the outer ramp, > 100 mwd. Outer-ramp sediment is also rich in planktics, with a rippled sediment zone between 80 and 120 mwd. A limestone pavement was encountered locally to 282 mwd. The limestone is generally poorly cemented skeletal material and ooids/peloids in micrite matrix/ cement.

When viewed at the largest scale, aside from the strandline itself, the major break on the seafloor is an escarpment, the base of which lies at 125 mwd. In shallower waters, the sediments are mostly mud free, typically swept into sub-aqueous dunes or textured by ripples.

Integration of information from Jones (1973) and James *et al.* (2004) permits separation based largely on sediment composition, of eight sedimentary facies (Fig. 4). Particles in these facies are biofragmental, oolitic and peloidal grains, carbonate tubes and terrigenous clastics. These grains are not coeval, but a mixture of relict, stranded and Holocene elements. There are two types of relict grains: (1) skeletal intraclasts – typically fragmented to usually well-rounded altered and infilled skeletons; and (2) lithic intraclasts – angular to locally rounded clasts of cemented grainstone, packstone or wackestone of metastable carbonate mineralogy. These particles are a ubiquitous component of Australian continental shelf sediments south of North-west Cape and across the cool-water carbonate province of the southern margin (Collins 1988; James *et al.* 1992, 1997, 1999, 2001). They are interpreted as having formed during former highstands, specifically Late Pleistocene MIS 3 and 4 highstands (Fig. 5), when sea level was ≈ 50 m lower than today and the shelf was intermittently submerged (James *et al.* 1997). In contrast, stranded

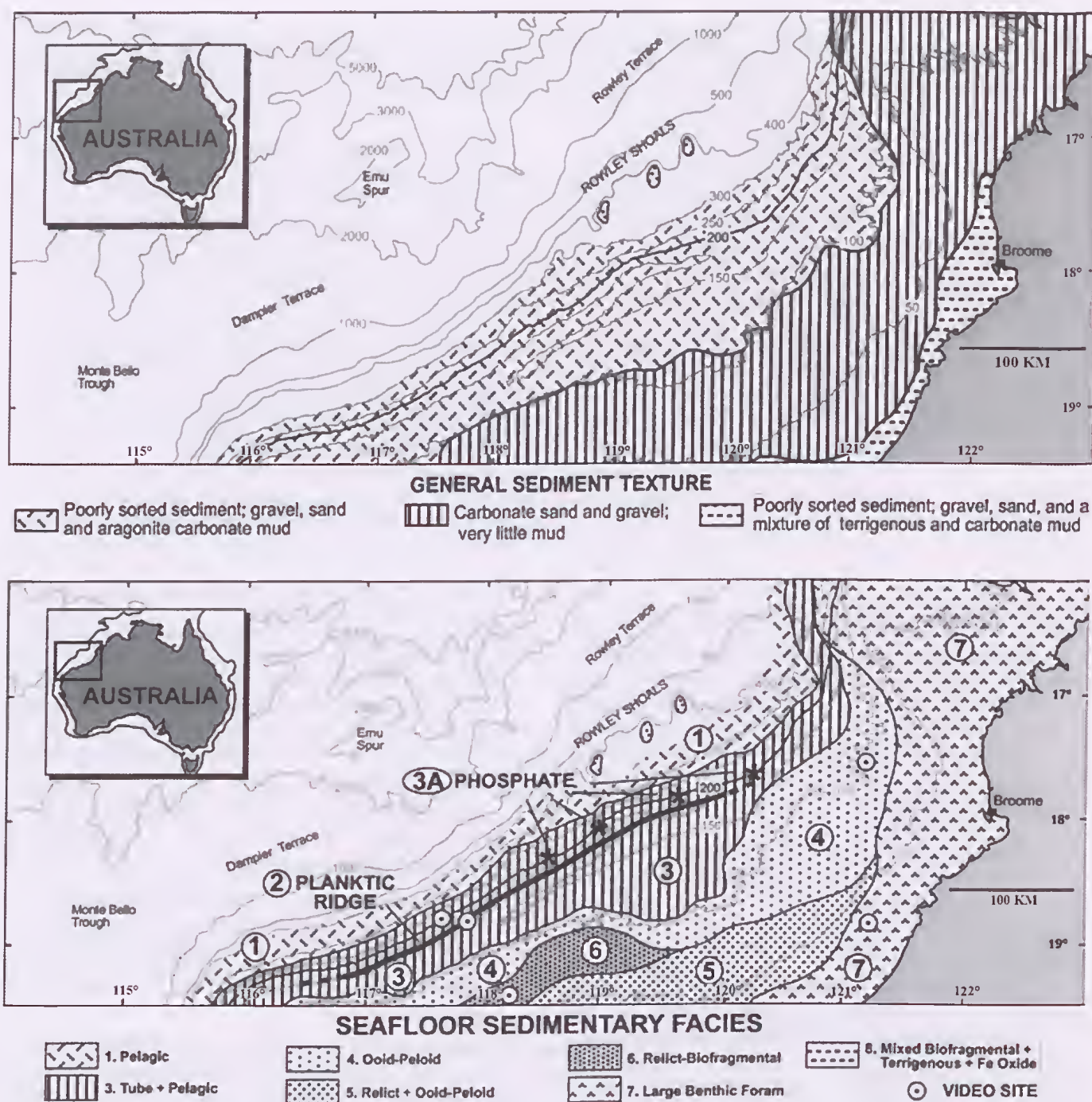


Figure 4. A. General sediment texture, and B. Seafloor sedimentary facies of the North West Shelf, modified after James *et al.* 2004.

grains are generally lightly stained, mildly abraded, younger than relict particles, but clearly out of equilibrium with their modern environment (James *et al.* 1997, 2001). The most obvious of these grains are coralline algae and ooids in water depths > 40 m. Such particles are interpreted as having formed in shallow water and having been stranded by rapidly rising sea level during the latest Pleistocene and Holocene.

The following facies are present on the outer ramp (see Fig. 4): –

Facies 1 – Pelagic sand and mud, Facies 2 – Pelagic ridge sand, Facies 3 – Calcareous tube gravel–pelagic mud, Facies 3A – Phosphate subfacies. The mid-ramp is

dominated by Facies 4 – Ooid/peloid sand, Facies 5 – Relict intraclast, ooid/peloid sand and gravel and Facies 6 – Relict intraclast, biofragment sand and gravel. The two main inner-ramp facies are: Facies 7 – Benthic foraminifera sand and gravel, Facies 8 – Mixed biofragmental–terrigenous–iron oxide sand (Facies 8: NWS region only). These facies continue as contour – following belts southward onto the adjacent NWS.

Origin of Particles-Relict Sediment: Relict grains are important parts of the sediment on the mid-ramp in water depths of < 150 m and most abundant (> 50% of sediment) between 80 and 40 mwd. The brown to orange to yellow-stained particles are clearly distinguishable

under the petrographic microscope using a combination of transmitted and reflected light. The brownish material is a complex mixture of clay minerals, iron oxides, aragonite and Mg--calcite manifest as either microcrystalline sediment or alteration of carbonate particles.

Stranded sediment: The most obvious of these grains on the NWS are ooids and, by implication, peloids. Some biofragments may also be stranded, but there is no clear way of telling which ones have such an origin.

Ooids are particles which range from fresh and white to locally beige in colour. Those that are white are typically polished. They are spread across the shelf from 30 to 300 mwd (Fig. 4) but focused between 60 and 150 mwd (peloids 60–150 mwd; ooids 60–135 mwd).

Ooids are generally fine to locally medium sand size, 0.25–0.75 mm in diameter, occasionally with a well-developed cortex, but most commonly with only superficial coating on a peloid core. The nucleus is also locally quartz grains inboard or benthic foraminifera, echinoid grains or bryozoans outboard. Scanning electron microscopy shows that the cortex comprises layers of tangentially and randomly oriented aragonite needles. Radiocarbon dating indicates that the ooids formed over a narrow time frame, 15.4–12.7 ka. Incremental dating of the cortex of three ooid populations points to growth occurring over ≈ 2000 years.

Peloids are generally < 2 mm in size, spherical to ovoid in shape, composed of microcrystalline carbonate and of two types (Jones 1973). SEM analysis of these peloids, some of which are ooid cores, indicates that they

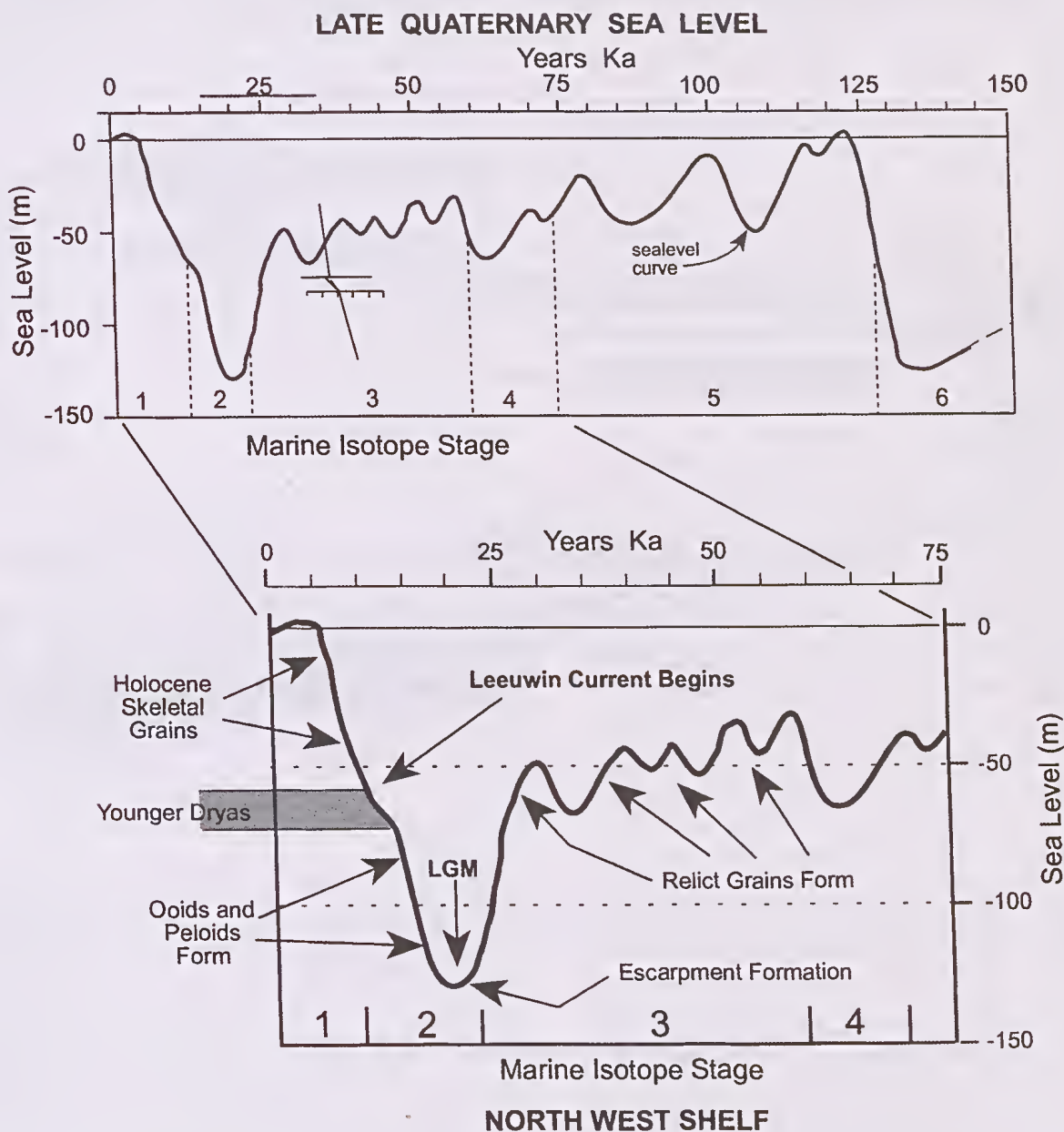


Figure 5: Late Quaternary sea level and expanded portion over the last 75,000 years showing significant events and periods of particle formation on the North West Shelf (after James *et al.* 2004).

are composed of aragonite needles, like those forming the ooid cortices. A few are also micritised skeletal grains. Some peloids are stained and so are relict, unlike the ooids. The close association between ooids and peloids implies a common environment of formation and geological age. Open marine ooids with an aragonite cortex typically form in shallow, tidal-dominated settings in water depths of less than 5 m (Simone 1980). More specifically, ooids reflect formation in environments of somewhat elevated salinity, for example on the Bahama Banks and the Persian Gulf, and in extreme conditions, as at Shark Bay (Logan *et al.* 1970). The rate of ooid growth is similar to that determined from the Bahama Banks (see discussion in James *et al.* 2004).

The period 15.4–12.7 ka corresponds to the period of rapid sea-level rise during meltwater pulse 1A (mwp 1a) associated with the first phase of post-Last Glacial Maximum (LGM) deglaciation (Jensen & Veum 1990), before Younger Dryas cooling (Fig. 5) and slowed sea-level rise. Comparison with the Barbados curve (Fairbanks, 1989) indicates that sea level would have risen from what is now ≈ 105 to ≈ 70 mwd during this time. Specifically, it would have rapidly submerged the escarpment and spread across the wide sea floor above the crest of the cliff, creating an expansive, shallow environment. Increased aridity and wind speed over continental Australia during and immediately after the LGM, with strong offshore winds in the NWS region (Prell *et al.* 1980; Williams 2001), would have increased evaporation, thus promoting ooid formation. Such an interpretation, of evaporative Bahamian/Persian Gulf-like shallows, also explains, in part, the association of ooids and peloids because, in the Bahamas platform margin, ooid facies also coincide with peloid lithification (Purdy 1963). Oxygen isotopic compositions of ooid cortex aragonite indicate lower $\delta^{18}\text{O}$ values with decreasing age, reflecting either warming or, more likely, decreased sea-water salinity. Analysis of clays in the region (Gingele *et al.* 2001a, b) suggests that the onset of Leeuwin Current flow, and attendant less saline sea water, began ≈ 12 ka. Thus, ooid and peloid formation is interpreted as having taken place in shallow evaporative shelf environments during mwp-1a, but as having been arrested by initiation of the less saline waters of the southward-flowing Leeuwin Current during mwp-1b (James *et al.* 2004).

Biofragmental particles: The association, in general terms, is foramol (foraminifera and molluscs) in character with accessory bryozoans, typical of a heterozoan assemblage (James 1997). Yet this is too simple a classification. Inshore, to depths of ≈ 30 m in the Barrow and Dampier sectors, the environment is one of coral reefs, bryozoans and macrophytes, together with large (symbiont-bearing) foraminifera. This is an unusual consortium – part photozoan and part heterozoan. There are no ooids here, and the calcareous green algae are not calcified. It is reminiscent of the Houtman Abrolhos reefs far to the south (Collins *et al.* 1997; James *et al.* 1999). Offshore, in waters > 40 mwd, the sediment is a heterozoan assemblage with large benthic foraminifera decreasing seaward, a subtropical sediment (James 1997).

Tube facies and phosphatisation: The calcareous tubes (Facies 3) appear to post-date the sediments in which they lie. Foraminifera in the tube wall sediment are latest Quaternary in age. Radiocarbon dating of bulk sediment

from the tube walls yields ages of 9.9 and 25.1 ka. Given that the sediment probably contains material of different ages, these results indicate that tubes are < 9.9 ka old, but the exact age is uncertain.

The sediment in which the tubes are developed has several very shallow-water proxies, particularly the bivalve *Anadara*, the grass meadow bivalve *Piua* and zooxanthellate corals, all pointing to an inner-ramp environment. This environment, now in water depths > 120 m, most probably formed during the LGM lowstand (MIS 2) about 20 ka (Fig. 5).

$^{87}\text{Sr}/^{86}\text{Sr}$ values for seven teeth and bones in the same sediment average 0.709174 (range 0.709143–0.709294), indicating that they are Late Pleistocene to Holocene in age (cf. Farrell *et al.* 1995). This age is in accordance with the relatively young age of the tubes upon which phosphate has precipitated. These ages of the tubes imply that arrested sedimentation, iron and phosphate precipitation and accumulation are ongoing today. Thus, this outer-ramp region is an area of weak upwelling and/or phosphatization resulting from Fe-redox cycling within the sediments (cf. Heggie *et al.* 1990).

Planktic sediment ridge: This elongate feature, first documented by Jones (1973), is of interest because of its persistence through time. Sea-floor samples are always pelagic sediment, particularly pteropods, with a fine-grained benthic component. Surface ripples indicate that sediment movement is to the south. Radiocarbon dating of pteropods and planktic foraminifera from two localities yields ages of 0.35 and 9.2 ka (thousand years), confirming the contemporary age of the material.

The structure is interpreted here as a high surface productivity phenomenon. The most likely explanation is that it corresponds to a zone of near-surface shear between the Leeuwin Current and Indian Ocean Water, thus promoting upwelling and nutrient enhancement.

Kimberley and North West Shelf Surface Sediment and Processes

The sediments are palimpsest, with diverse particle types of different ages, variably mixed by biological and hydrodynamic processes to form a complex facies mosaic, some of which contains many particles that are out of equilibrium with the present sea-floor setting. A summary of ramp sedimentation is shown in Figure 6 (after James *et al.* 2004).

Implications for the Understanding of Ramp Sedimentation

The Kimberley and NWS is a carbonate ramp on the scale of such carbonate realms as the great Bahama Bank and southern Persian Gulf. Almost all attributes are determined by regional oceanography, in sometimes unexpected ways. Inner-ramp facies on the NWS are a complicated mix of photozoan and heterozoan elements, reflecting an oligotrophic oceanic setting repetitively perturbed by the influx of fine sediment and nutrients from land. The high energy of the marine system sequesters these terrigenous clastics adjacent to the shoreline, and they are not transported offshore.

Saline water outflow along the sea floor, the result of evaporation on the inner ramp, appears to have subdued

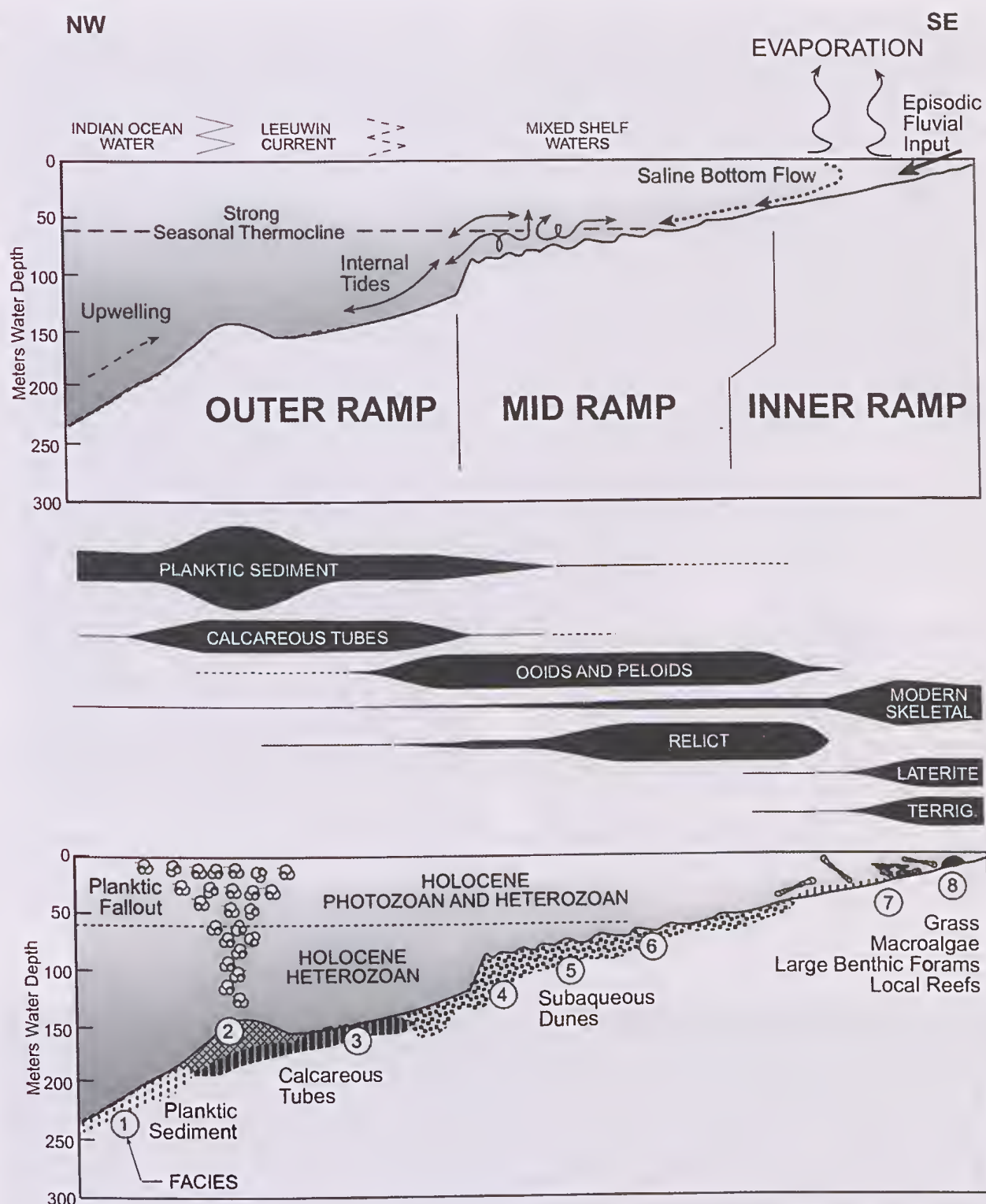


Figure 6. Summary diagrams illustrating (top) the major oceanographic-climatic factors affecting shelf sedimentation, (middle) the spatial distribution of major particle types across the ramp and (bottom) major ramp features and sedimentary facies (see also the facies map in Fig. 4). After James *et al.* 2004, Figure 11.

or arrested modern benthic carbonate production on much of the mid-ramp. This may be, in part, why the mid-ramp is not more distally steepened.

Changing late Quaternary oceanography has had a profound effect on NWS carbonate sedimentation. During the last global sea-level low-stand and early parts of the subsequent transgression, the NWS was a site of

warm-water carbonate sedimentation, with strong offshore winds probably enhancing upwelling and evaporation. There is clear evidence that, during the initial stages of sea-level rise, ooids and peloids, a classic warm-water facies, developed across many tens of kilometres of the then shallow shelf. Yet, this sedimentation ceased ≈ 12 ka, when the lower salinity

Leeuwin Current began to flow strongly. It is this change in oceanography that probably resulted in a shift to the present dominance of skeletal carbonate production. In this situation, carbonate production has not been able to keep pace with rising sea level, implying an overall reduced sedimentation rate that has left the seafloor veneered with a mixture of old and new deposits, many of which are out of equilibrium with modern environments.

As the region illustrates: (1) the rapid rate of sea-level rise stranded shallow-water sediments; (2) the changing oceanography altered the character of the carbonate factory from photozoan to heterozoan (and mixed heterozoan/photozoan on the inner ramp); and (3) the high-energy (waves, swells, cyclones, internal tides) mixed sediments formed at different times during transgression. This situation is most obvious on the NWS because the area is near the temperate–tropical carbonate system boundary, and so dissimilar carbonate sediments from different systems are mixed. This large oceanic ramp, located in the tropics, yet near the temperate carbonate realm, is one of the largest such systems in the modern world. The surficial carbonate sedimentary facies display complexities that are largely explainable in the context of modern and late Quaternary oceanography.

Reefs and Banks of the Oceanic Shoals Biozone

Coral reefs are widespread along the Kimberley coast and comprise a major geomorphic feature along the continental shelf edge from 12°S to 18°S (Fig. 7). Fringing reefs intermittently occur along an extensive portion of the coastal region. These reefs are very poorly known and endure in a remarkably inhospitable environment with high sediment input and high hydrodynamic energy, but they have been suggested to be of international significance and are in need of intensive study (Chin *et al.* 2008).

Whilst the understanding of the fringing reefs of the Kimberley still remains a gap in our knowledge, described here are aspects of the morphology, internal architecture and Quaternary growth history of some of the offshore reefs within the Oceanic Shoals Biozone (Fig. 3; Table 1) which borders the continental shelf of the Kimberley region, based on published reports, seismic and limited core data, providing the first account of Quaternary reef architecture for some of the northernmost coral reef systems of Western Australia. These reefs (except Scott Reef; Collins *et al.*, this volume) remain relatively poorly known geologically since the pioneering studies of Fairbridge (1950), unlike the well studied Great Barrier Reef, on Australia's northeast coast (Hopley *et al.* 2007).

Reefs and shoals of the Sahul Shelf

Marginal to the Sahul Shelf (north Kimberley) and close to Timor are a series of isolated submerged shoals (Echo Shoals, Big Bank and Karnt Shoals) (Fig. 7; Heyward *et al.* 1997). The shoals formed a string of banks seaward of the palaeo-coastline, some with vertical relief of over 300 m, and were drowned in the last 20,000 years (Lavering 1993), terminating the major carbonate

production derived from corals. Thereafter, the carbonate accumulation that maintains many of the banks derives from the *in situ* growth of *Halimeda* and accumulation of its fragments with contribution from a diverse reef biota of lesser abundance (Heyward *et al.* 1997). The interaction of subsidence and sea level rise has presumably drowned coral reef growth, and without the constraints imposed by the photic limits applicable to corals *Halimeda* has become the major constituent of reef/bank growth in this region.

Ashmore Reef

Ashmore Reef is an ovoid platform reef at 12°20'S on the edge of the shelf at the Browse/Bonaparte basin boundary (Fig. 7). Built on antecedent topography, the reef is the largest emergent reef and has the highest biodiversity of any reef on Australia's western margin (Glenn & Collins 2005). There are three vegetated cays, two lagoons separated by a calcareous rise, numerous patch reefs, intertidal flats, seagrass beds, lineated and non-lineated reef flats, algal pavement, and a precipitous reef front with spur and groove. The reef growth model has 3 phases (Glenn & Collins 2005): 7.5–6–5 ka: subtidal reef growth over antecedent topography during rapid sea level rise; 6–5–4–5 ka: transitional growth, catching up to slowly rising sea level; 4–5 ka–present: lateral extension phase, with broad reef flats developing as the reef front/crest reached sea level. Holocene reef thickness is about 20 metres.

Seringapatam Reef

An annular reef 8 km long and 9.4 km wide encloses a lagoon 20 m deep, with a narrow northeast passage connecting it to the ocean (Berry & Marsh 1986). The western reef is broader than that on the east (1500 m vs. 1200 m). There is a well developed reef crest boulder zone, a coralline algal rim, spur and groove zone, with coralline algal-covered grooves, then living coral to about 30 m (Berry & Marsh 1987). There are no seismic or other subsurface data available for this reef.

Scott Reef

One of the most significant offshore reefs is Scott Reef at 14°S (Figs 7, 8). This reef and the associated small carbonate platform grew along an old Miocene continental margin, and the reef has maintained its development despite rapid subsidence of the shelf edge since the mid-Miocene. The modern reef is subject to cyclones and bleaching (Smith *et al.* 2008; Heyward *et al.* 1997) and its remote location and distance from the coast (up to 400 km) positions the reef amongst the most pristine coral reef environments remaining in the world (Chin *et al.* 2008).

Scott Reef rises from depths of 400–800 m on the distal portion of a carbonate ramp, and is similar in setting to 'downslope buildups' (*sensu* Read 1985). It is a complex of two large isolated coral reefs separated by a deep channel; the pear-shaped North Reef and the crescent-shaped South Reef (Berry & Marsh 1986; Fig. 8). North Scott Reef is continuous except for two narrow passages, one in the southwest, and one in the northeast, with similar reef flat dimensions throughout. The outer reef flat is a mixture of scattered large boulders and

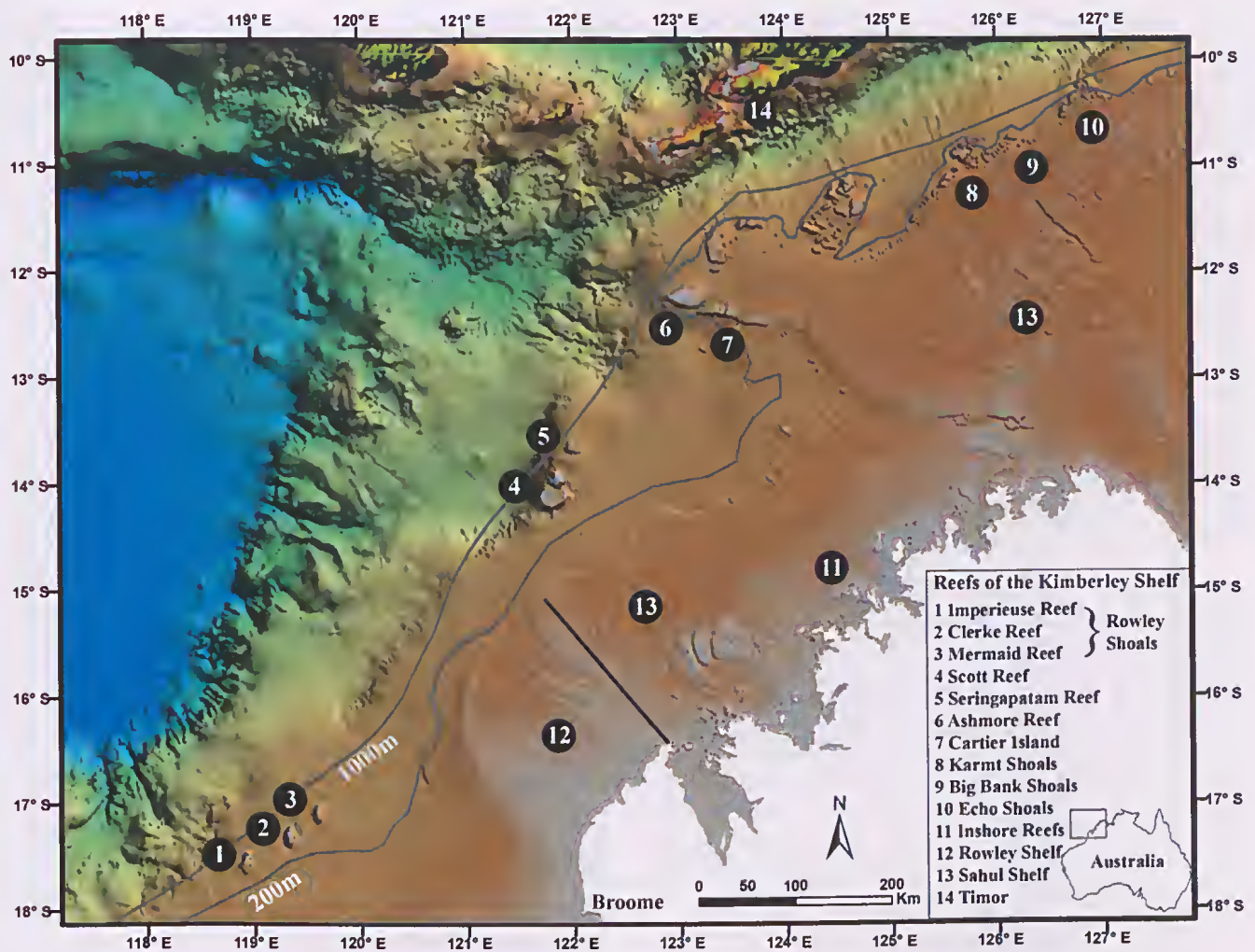


Figure 7. Location map of the Kimberley region, showing reefs mentioned in the text. Data for topography provided by Geoscience Australia.

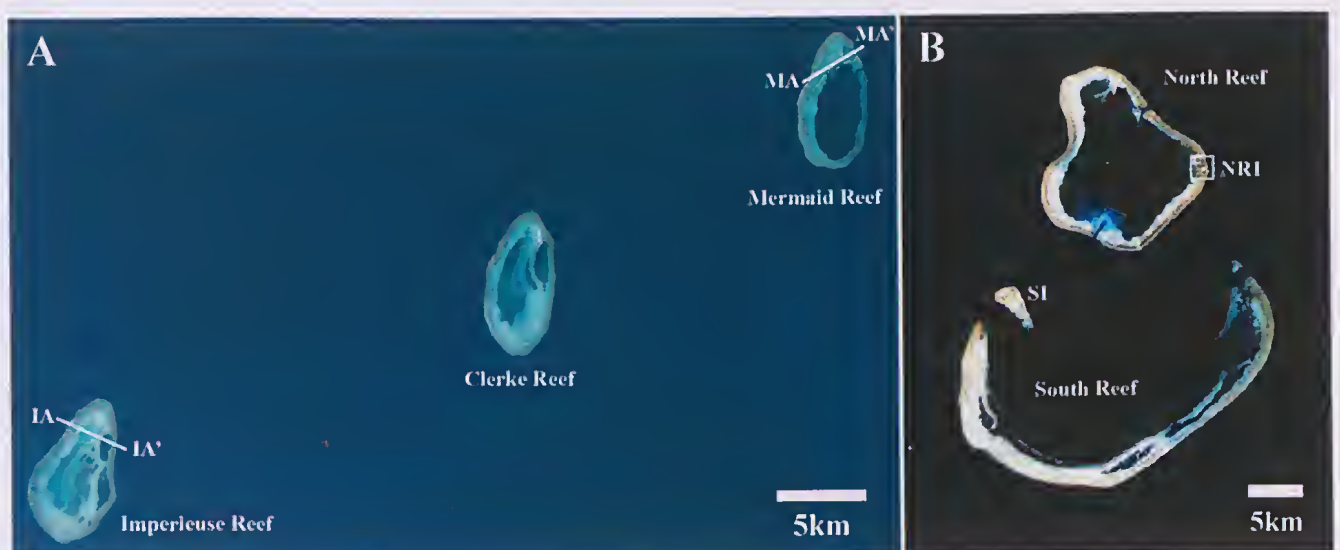


Figure 8. Landsat images of Scott Reef and Rowley Shoals. Location of borehole NRI is shown in North Scott Reef.

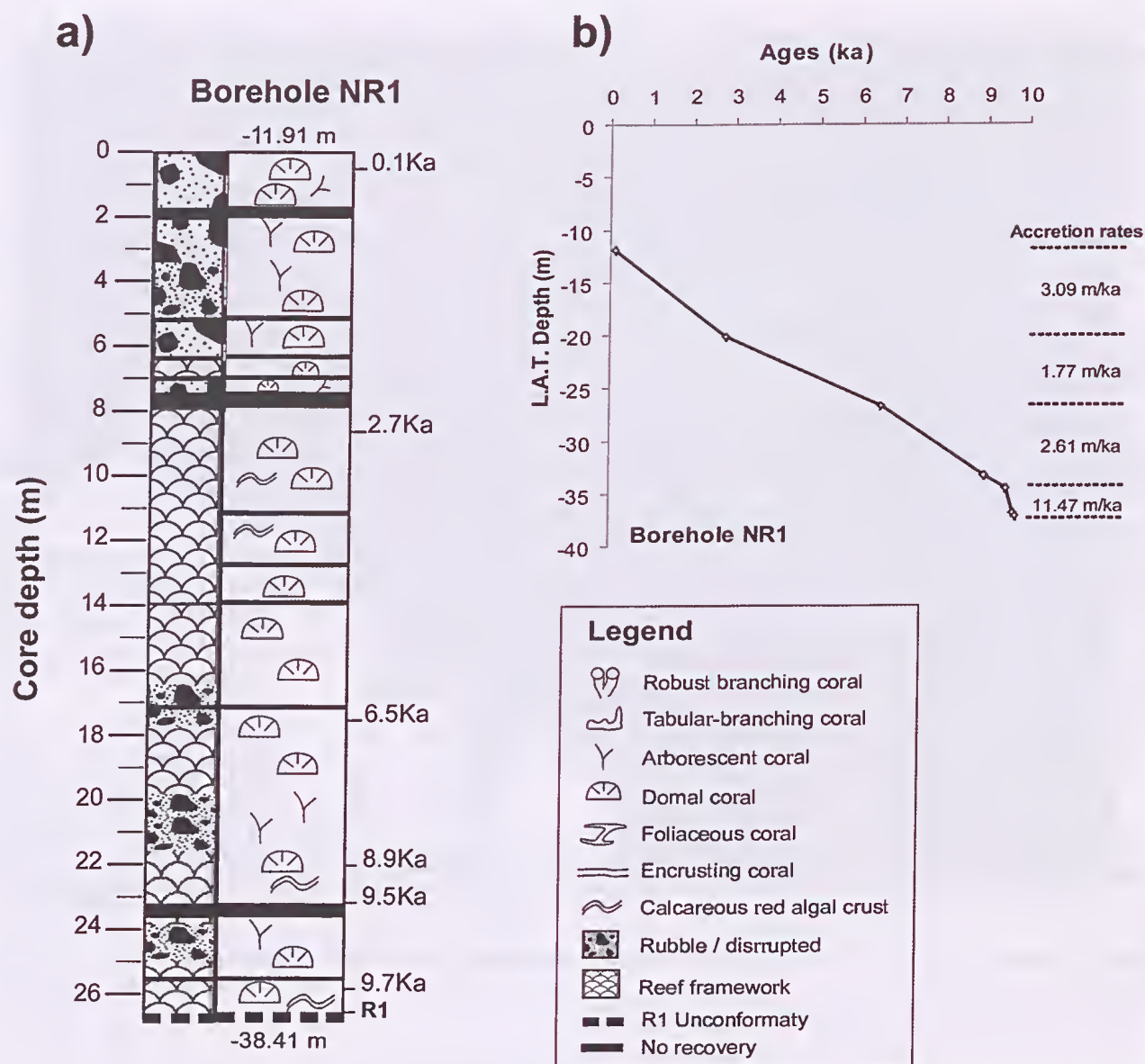


Figure 9. Summary of U-series dates for Holocene core NR1, North Scott Reef. A) Holocene chronology, reef community and lithology; b) Growth history curve for foreereef core site NR1, North Scott Reef. For core location see Figure 8.

occasional living corals. The outer reef gives way on its seaward margin to a gentle slope followed by an irregular outer slope with surge channels extending to 30 m and steep gradient to seaward. The inner reef has low coral cover, some algal turf, and lacks a distinct boulder zone. The back reef is deeper, with a more diverse coral fauna, and the lagoon is sandy with scattered corals (Done *et al.* 1994).

South Reef is open to the north, and is 27 km wide (east-west) and 20 km from north to south. The distance between the reefs is 5 km and the intervening channel is 400–700 m deep. The reef flat of the western part of South Scott Reef is over 2 km wide, and 600 m of reef flat is emergent at low water. Sandy Islet is a small, unvegetated sand cay situated atop a detached northwesterly portion of the reef. The eastern part of the reef is similar in morphology to the west reef, also with a detached sand cay, which is the only portion emergent at low water. The outer reef generally has encrusting

coralline red algae and minor corals, and the reef flat includes boulder rubble, sand flats, algal turf and minor amounts of coral. The back reef is sandy with scattered large *Porites* colonies, other corals and sparse seagrass. Lagoon depths inside South Scott Reef are 35–55 m (ca. 30 m in North Reef) and there are isolated coral knolls, sandy areas, and hard substrates with sponges and stunted coral communities (Done *et al.* 1994).

The Holocene reef section is composed of porous but relatively unaltered reef framework with lesser amounts of carbonate sediment; some intervals, particularly those of branching corals, are rubbly, partly as a result of accumulation of both framework and infill material (Fig. 9). The dominant frame builders in borehole NR1 (foreereef of North Reef) are communities of two types: arborescent (branching) acroporides, and domal (massive) corals mainly poritides; these exist as end member communities as well as in mixed associations. Reef initiation and early stages are characterised by

coralline red algal crusts and domal coral, with gradual increasing contribution of branching corals. The Mid to Late Holocene is dominated by domal corals, and this facies is replaced by arborescent and domal facies during the Late Holocene to present.

Uranium-series chronological data obtained for NR1 is in agreement with stratigraphic data and the expected position of the pre-Holocene unconformity (R1), corresponding to Marine Isotope Stage 1 (MIS1), at about 26.5 m core depth (-38.41 m relative to Lowest Astronomical Tide; LAT) (Fig. 9). The earliest dated settlement of reef building coral community recorded for the borehole is 9.7 ka at 25.75 m core depth (-37.16 m LAT depth), followed by subsequent development during the Holocene.

The average accretion rate for the Holocene section of borehole NR1 is calculated as 2.64 m/ka. However, the accretion rate curve suggests four distinct phases of reef development (Fig. 5b; Table 1): an initial and faster development from reef initiation to 9.47 ka, characterised by an accretion rate of 11.47 m/ka; accretion rate gradually reduces to a minimum of 1.77m/ka during middle Holocene (6.4–2.7 ka), returning to increase to 3.09 m/ka from late Holocene to present (Fig. 5b).

Variations in the accretion rates during the Holocene can be explained by the dominant coral communities during the middle Holocene (Fig. 9a, b), which is characterised by slow growing domal corals, such as the genus *Porites*. In contrast, higher accretion rates were recorded when there are greater proportions of arborescent forms (see also Blanchon & Blakeway 2003; Montaggioni 2005). Whilst the faster accretion rates recorded during reef initiation were expected, the more consistent slow rates for most of the Holocene are more representative of the overall Holocene reef development such as commonly found in Indo-Pacific reef margins (Montaggioni 2005), resulting in the generation of a 25 m thick Holocene section at Scott Reef. For a fuller discussion of Scott Reef see Collins *et al.*, this volume).

Rowley Shoals

The Rowley Shoals (Figs 8, 10) comprise a group of three offshore isolated reefs, the Mermaid (17°06'S – 119°37'E), Clerke (17°19'S – 119°21'E) and Imperieuse (17°35'S 118°55'E – 17.583°S) reefs. Described as the most perfect morphological examples of shelf atolls in Australian waters (Fairbridge 1950), the three shoals have similar dimensions, shape, orientation and distance apart, and all rise from the distal ramp of the North West Shelf. From northeast to southwest the reefs rise from progressively shallower depths on their landward sides; Mermaid Reef from 440 m, Clerke Reef from 390 m, and Imperieuse Reef from 230 m. Each atoll (length range 15–17 km, width range 7–9 km) has north-south orientation, is pear-shaped with the narrower end to the north, and has a reef which encloses a single central lagoon which is ovoid and relatively deep in Mermaid Reef, but becomes increasingly shallow and segmented in Clerke and Imperieuse reefs. About two thirds of the way up its eastern side, each system has a narrow passage (or passages), through which tidal flushing and sediment exchange occur (Berry & Marsh 1986).

Mermaid Reef (Fig. 10) has, on its western side, an outer reef flat (0.5 km wide) which is exposed at low tide, and a back reef of similar width, backed by a 1 km wide sand flat. The eastern margin is only 0.6 km wide and the sand flat is absent. The western outer reef slope has well-developed spur and groove, the outer reef has slow-growing coralline red algae and corals, while the back reef flat has a cover of living and dead coral and algal turf (Berry & Marsh 1986). At Clerke Reef the shallow (<10 m) lagoon is segmented into three parts by sand sheet development (Collins 2002). Imperieuse Reef has a lagoon partitioned into three basins by sand sheet development but the two along the eastern edge are deeper than the larger, central basin which is extensively infilled by a meshwork of coral growth, composed of flat-topped coalescent reef with intervening sand-floored depressions (Collins 2002). The coral assemblages described for Scott Reef by Done *et al.* (1994) are also recorded at Rowley Shoals. Differences in reef morphology, hydrodynamic exposure and ponding are reflected in the assemblages.

The Rowley Shoals are similar in gross morphology (ovoid shape, with annular reef and central lagoon; similar length and width) in their down-ramp setting (but they rise from increasing depths to the northeast, 230 m at Imperieuse to 440 m at Mermaid Reef) and wind, wave and tidal regimes. They differ in morphology by an increasing degree of lagoon infill from northeast to the southwest, from the open, ovoid and 20 m deep Mermaid lagoon, through the partially infilled and partitioned Clerke lagoon, to the shallow, more fully infilled Imperieuse lagoon (Fig. 10).

It could be argued that different degrees of sediment retention or export from the lagoons through leeward channels could influence lagoon infilling, and a plume of expelled lagoon sediment was detected in nearby seafloor samples at Mermaid Reef collected at 400 m depth (Collins 2002). Similar northeasterly leeward channels at Clerke and Imperieuse Reefs are poorly developed, only a few metres wide, and transport much smaller sediment loads, so these lagoons apparently retain far more sediment than Mermaid Reef.

Seismic profiles for Mermaid and Imperieuse Reefs show the pattern of reef growth in both, with the Holocene reef growing in the accommodation (space) provided by a saucer-shaped, subsided, last interglacial reef. The calculated subsidence rate since the last interglacial (Fig. 10) is 1 m/6000 y, comparable to that of Scott Reef. However, there is a striking difference in the depth of the last interglacial reflector in the lagoon, which is uniformly 37 m below sea level in Mermaid Reef, but only 18 m below sea level in Imperieuse Reef (Fig. 10). Aside from indicating differential subsidence since the last interglacial (ca. 125 ky ago; see Fig. 11), assuming the lagoon floor elevations were initially similar, these data indicate that the accommodation available for Holocene reef growth and lagoon infill at Imperieuse Reef was only 50% of that available at Mermaid Reef, and this is a key long term control on the different amounts of lagoon infill during the same time interval observed between the two reefs, and the resultant morphological series (Fig. 10).

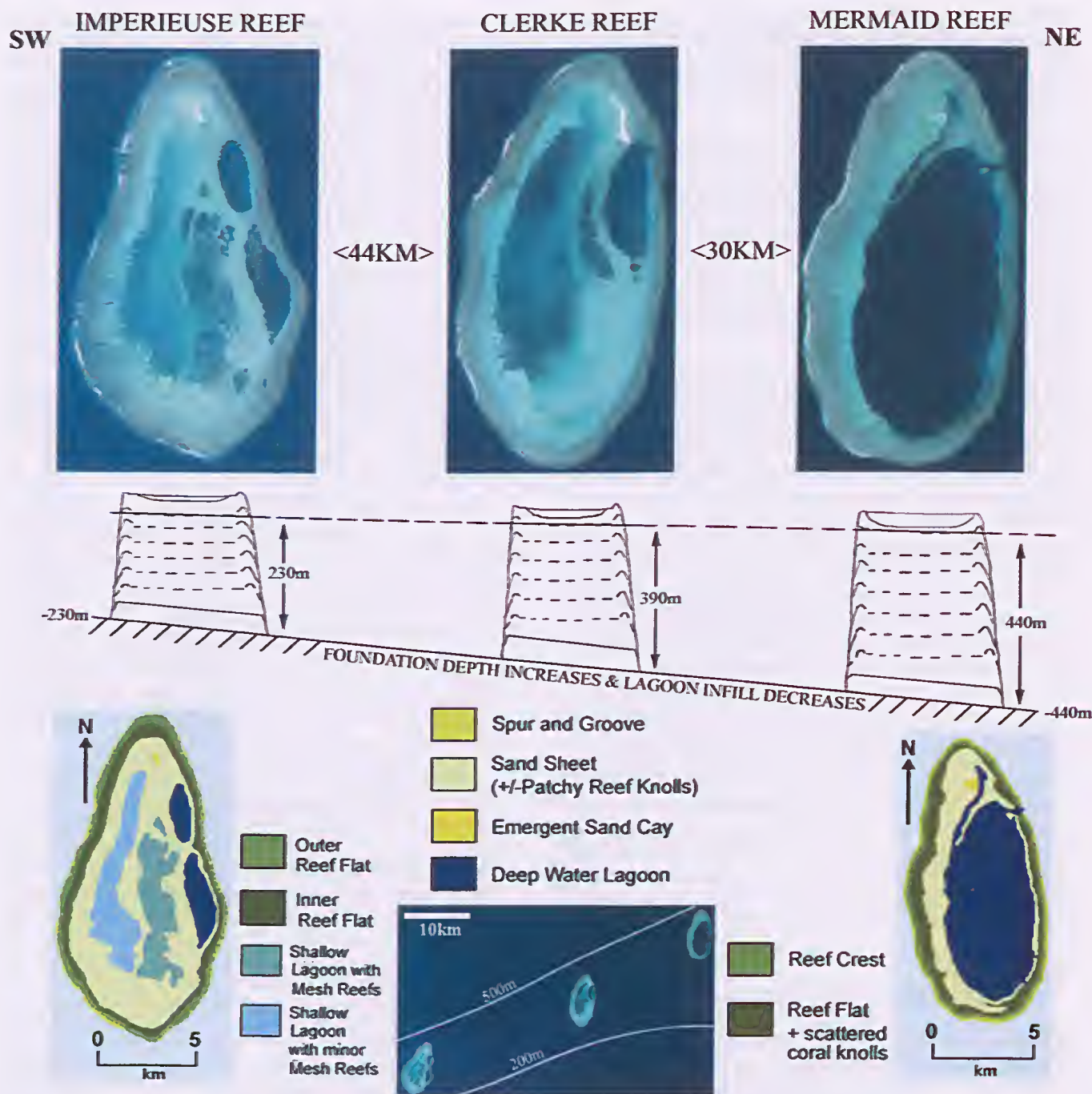


Figure 10. Landsat images, substrate maps, plan and cross section of the Rowley Shoals, the section redrawn from seismic data. The pattern of decreasing lagoon infill northward reflects differential subsidence since last interglacial time (the previous event of reef growth to the Holocene reefs; 37 m for Mermaid but only 18 m for Imperieuse Reef) so that infilling of available space is near complete in the latter, but remains incomplete in the former. Note the differing elevations of the shelf surface on which the shoals have developed, and the vertical disparity between these apparently identical platforms which (assuming similar initial ages) likely reflects a higher long term subsidence rate, and greater sustained vertical growth for Mermaid Reef. (Seismic data from Collins 2002).

Discussion

This paper has attempted to provide an earth science perspective from which to consider present and future issues for marine science and management of the unique Kimberley area. It is clear that the gathering pace of offshore activities will require greater attention to such considerations in the coming years. The hydrocarbon resource potential and long term exploration and production of the Browse and Bonaparte Basins is

evident from existing and proposed field developments in a global climate of declining reserves and increasing demand for gas in our region. Much of this activity lies within the deep waters near the continental margin in the Offshore Shoals Bioregion, but impacts on other regions may follow.

With the onset of plate collision between the Australian and Eurasian plates since Miocene time, (subsidence rate of 15–20 m/Ma, Sandiford 2007)

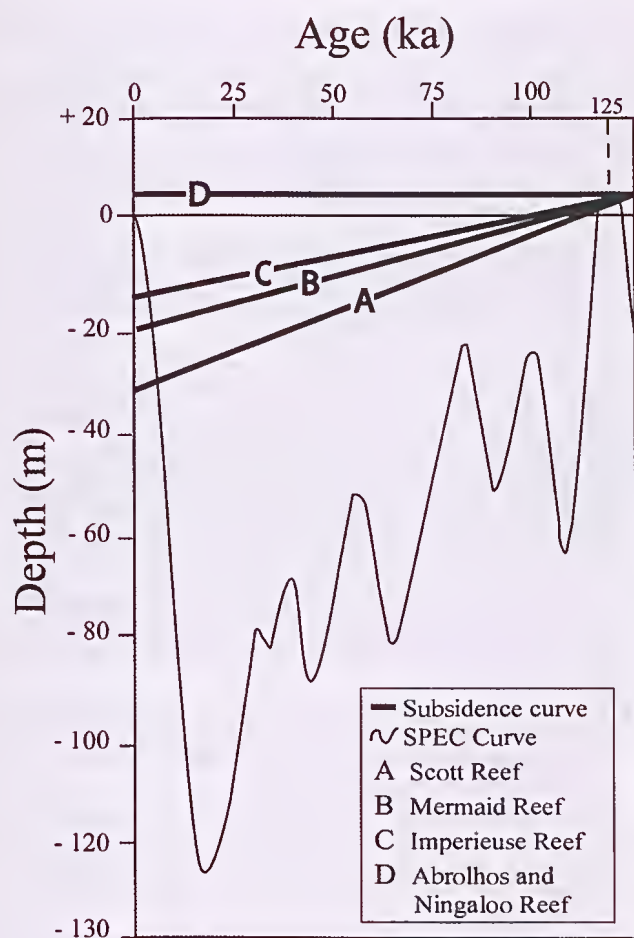


Figure 11. Global sea level curve and subsidence rates determined from seismic data for NWS reefs, based on depths of last interglacial surface. Sea level curve based on Chappell & Shackleton (1986).

structural remnants such as the Scott Plateau, Rowley Terrace and Sahul Rise have provided suitable substrate for coral and *Halimeda* build-ups offshore, and despite the sea level oscillations of the Pleistocene and the long term subsidence of the continental margin these reefal buildups have persisted as long lived structures which have vertical growth of as much as 400 metres.

Overall the surface sediments of the NWS are sand and coarser dominated carbonate, and contain abundant relict material with authigenic phosphate and glauconite components, the latter reflecting upwelling. Deep-water sediments are planktic muddy sands while the shelf materials are skeletal, peloidal and oolitic. The coarse fraction (> 2 mm) is entirely skeletal, consisting of molluscs, benthic foraminifera, bryozoans, echinoids, calcareous algae, corals, benthic foraminifera, and bivalves. They are mixtures of relict, stranded and bioclastic sediment, and reflect both changing sea levels and oceanography interacting with biodiversity. The onset of the Leeuwin Current some 12 ka ago terminated deposition of precipitated particles (ooids, peloids) and favoured bioclastic production.

Unlike the drowned reefs, now *Halimeda* shoals of the Sahul Shelf further northward, all of the Kimberley coral reefs described here have been able to survive as resilient

reef systems and generate high coral buildups despite their position bordering a subsiding ramp margin. In the case of the three Rowley Shoals differential subsidence can be linked to a transitional series of lagoon infill and geomorphology in these otherwise similar oceanic atolls.

The core described for North Reef is significant because it serves to confirm previous seismic interpretations, but has additional importance. Ocean-facing reef cores are uncommon from high energy settings due to the difficulty of the logistics involved in their collection, and the core data presented here is therefore an important contribution to the characterisation of the fore-reef zone of shelf edge reefs. The Indo-Pacific reef growth phase (termed RG11) was characterised by moderate rates of sea level rise of 10mm/year from 11 to about 7–6.5 ka BP until sea level stabilization at or 2m above its present position (Pirazzoli 1996, Collins *et al.* 2006). Pre-Holocene accommodation was created at a calculated subsidence rate of 0.25m/ka (Collins 2002), and subsidence was an important control of overall reef morphology.

Coral reefs worldwide are under increasing threat from anthropogenically induced climate change including temperature-induced coral bleaching (Hoegh-Guldberg 1999; Wilkinson 2008) which is often exacerbated by human activities. The remoteness of the Kimberley region provides little protection from the former but is likely to continue to limit the latter impacts, however these may increase in future. Further biological and geological research is needed in this region to examine reef response to past climate and sea level change and to provide analogue information for future climate change management.

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Notes on the origins and biogeomorphology of Montgomery Reef, Kimberley, Western Australia

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Abstract

Montgomery Reef, lying at the boundary of Camden Sound and Collier Bay is a very large rock platform (c. 400 km²) in an open sea setting of the Kimberley Bioregion, Western Australia. It is not a coral reef platform in the strict sense but an ancient terrestrial structure, probably a flat-topped mesa, with a Holocene veneer of marine biogenic sediments superimposed over inherited terrestrial geomorphic features. The eastern end of the reef, at least, has base rocks (beneath the corallgal veneer) of dolomite, underlying quartz sandstone mapped as Pentecost Sandstone, an upper member of the Paleoproterozoic Kimberley Group. The dolomite is an unrecognised formation and its well preserved stromatolites are undescribed. Although the coral fauna on the reef platform is moderately diverse, coral reef-building is located primarily in the impounded pools lagoons of the reef platform. There is very little coral growth on the reef-front. An unusual feature is the relative importance of rhodoliths that form massive containment banks around the perimeter of the reef and are responsible for creating the high lagoon habitats. Field observations suggest that rhodoliths may be the most important contemporary reef-builders on Montgomery Reef with very high primary production inferred.

Keywords: Montgomery Reef, Holocene reef growth, rhodoliths, corals, stromatolites, biogeomorphology

Introduction

Montgomery Reef is a very large, flat-topped geomorphic structure whose platform surface is exposed at low tide. It has an estimated area of c. 400 km², located in open sea at the Collier Bay-Camden Sound boundary about 15 nautical miles north of the Yampi Peninsula. Recent surveys of the modern reef fauna of the Montgomery Reef platform have been carried out by the Australian Institute of Marine Science and the Western Australian Museum, rendering this one of the better known reefs in the Kimberley in regard to its biota. However, its geology and reef-building processes remain undescribed. There have been various interpretations of the nature of the reef and its origins. Teichert and Fairbridge (1948) referred to it as one of several “large, rather irregular patches of reefs [that] rise in the deeply indented bays of the Kimberley coast”. Burbidge *et al.* (1991) noted that “the Montgomery Islands at the centre of the platform are surrounded by “sand flats and coral reef”. The Marine Parks and Reserves Selection Working Group referred to Montgomery Reef as “an extensive intertidal and shallow subtidal rock platform” (CALM 1994). Brooke (1997) described it as one of several large “carbonate bioherms” near the Kimberley coastline. This report considers the nature of the reef and its origins and reef-building processes on the basis of field observations made during a brief visit.

The geological and biogeomorphic history of Montgomery Reef and its biota have particular importance because its small islands have high cultural significance. O'Connor (1994) excavated material from an open habitation site on the largest of the High Cliffs Islands (Ngalanguru) and dated it at round 6,700 years B.P., indicating that the islands of this reef were populated by people with a specialised maritime economy soon after the end of the post-glacial transgression. Since that time, people lived there, at least periodically, until the “contact” period in the early part of the 20th century. It is said that these people, who were known as the Jaudibaia, spoke a distinctive dialect (Love, quoted by Tindale 1974) indicating a long independent heritage. The resources that supported this group were primarily those associated with the reef.

Methods

This report is largely descriptive, presenting field observations from a brief visit to Montgomery Reef by a party from the Western Australian Marine Science Institution [WAMSI] in August–September, 2009 aboard the W.A. Fisheries patrol vessel *P.V. Walcott*. Hyperspectral airborne imaging of Montgomery Reef, including tri-colour scanner and high resolution digital photographs of the study area commissioned by WAMSI were produced and processed by *Airborne Research Australia* and Curtin University Department of Applied Physics. These data provide the first high resolution

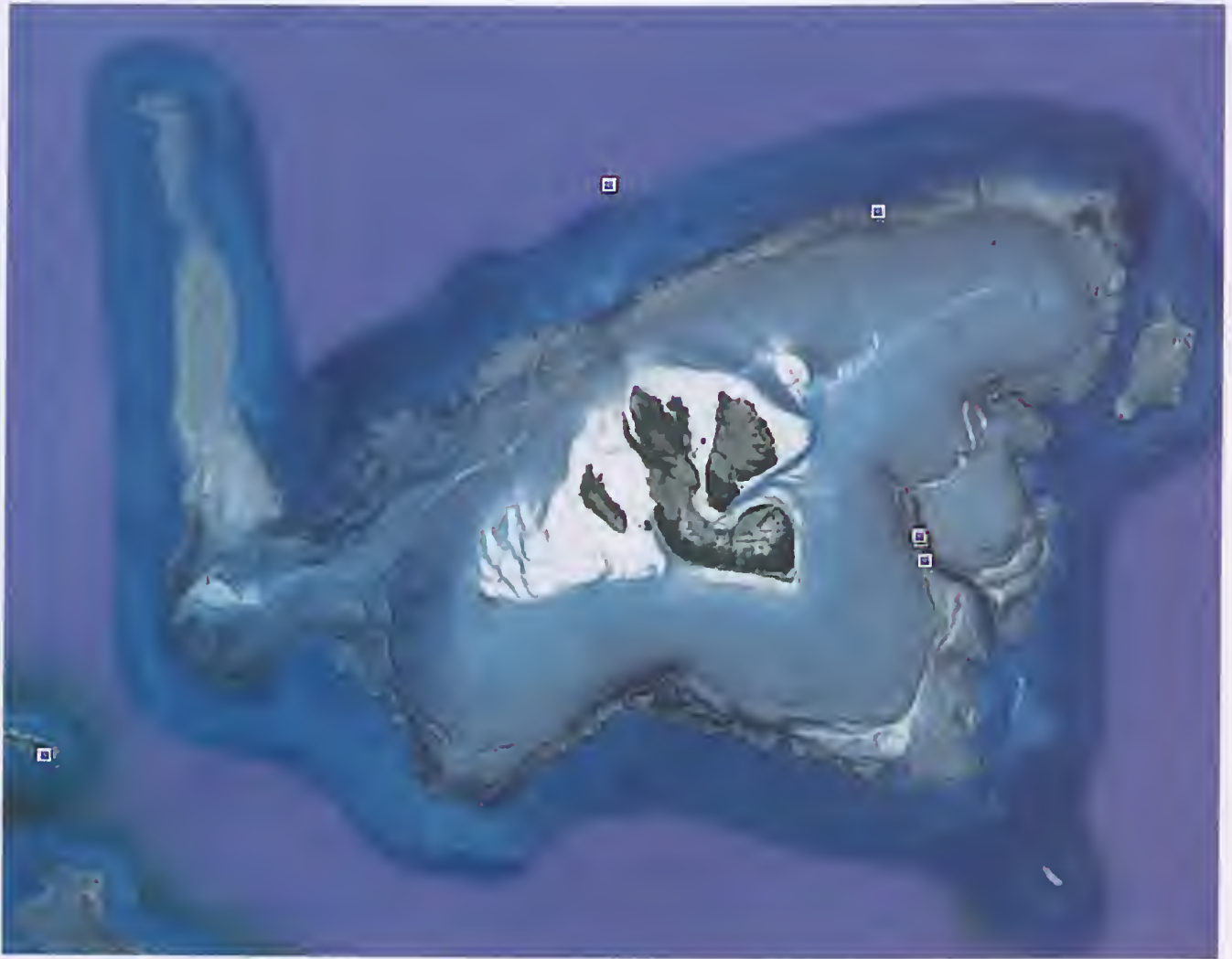


Figure 1. Montgomery Reef. Acknowledgements to Google Earth.

digital base map with 3 metre on ground resolution that can be further interrogated for detailed spectral information from the key “end members” including corals, algae, rhodoliths, sediments and mangroves.

Terminology

In this report *rock platform* is used as a geomorphic term meaning a reef structure that has a near-horizontal surface in the intertidal zone, the rock being of any kind. Such a platform surface may have been an outcome of erosional or constructional processes, or a combination thereof. Intertidal rock platforms are thought to be erosional and are often referred to as “wave-cut platforms” (Edwards 1958). A *coral reef platform* is one where the framework of the structure is constructed, *in situ*, by growth of coral and calcareous algae and the level of the platform surface is determined by limits to vertical coral growth. The term *coral platform reef* is a category of coral reef that lacks a lagoon and commonly has an oval outline, a central sand island and a flat intertidal surface. On the Kimberley coast there are many intertidal rock platforms of flat-bedded Proterozoic rocks that have a wedge of Holocene coral and algal growth and carbonate deposition at the reef-front, thereby

warranting the term *fringing reef*. Rock and coral reef platforms generally have a sloping lower-littoral *reef-front ramp* with a distinct *reef edge*, a *reef crest* and a mid-littoral *reef flat*.

As a geomorphic structure, Montgomery Reef and its parts do not fit, exactly, any of these terms and it is necessary to describe what is observed and use standard reef terminology with caution and explanation.

Results

General morphology of Montgomery Reef

Montgomery Reef has a horizontal but terraced surface within the intertidal zone, referred to here as the reef platform, and steep, cliff-like peripheral walls in the subtidal fore-reef zone. Three primary biogeomorphic units may be distinguished, the main reef, a north-pointing arm called The Breakwater at its western end, and a small satellite reef separated by a deep channel at its eastern end called High Clifty Reef (Fig. 1). There are several small islands on the platform. The Montgomery Islands comprise a cluster of low, mud islands at its centre, vegetated with mangroves and grassy flats and



Figure 2. High Clifty Reef with its five small islands, separated from the main Montgomery Reef platform by a deep channel. (Data courtesy of WAMSI and Airborne Research Australia, and images processed by Curtin University.)

largely surrounded by sand sheets. There are also eight small rocky islands on the eastern margin of the complex. They include five islands, known collectively as the High Clifty Islands, arranged around the eastern and southern fringe of High Clifty Reef (Fig. 2). The other three are located on or near the eastern margin of the main Montgomery Reef and are known as the dual Egret Islands (Fig. 3) (referred to as Jungadi by Roy Wiggan) and Wuljarlu Island (Fig. 4).

The form of the main reef platform is atypical. There is very little coral reef growth at the reef-front and calcareous algal growth appears to dominate biogenic carbonate deposition on the reef flat. There are some parts of the reef flat where rock pavement (with a crustose algal veneer) is exposed at low tide but most of its vast area (c. 350 km²) is occupied by a shallow lagoon and pools. The reef flat and its lagoon and pools are at two levels separated by an impoundment bank of rhodoliths, the upper level about 50 cm above the lower one behind the reef crest. There is no back-reef and in that respect Montgomery Reef resembles a very large coral platform reef. Some details are given in the following section on intertidal habitats.

Geology

The mainland coast and islands east and south of Montgomery Reef lie along the south-western margin of the Kimberley Basin, its rocks being upper members of

the Paleoproterozoic Kimberley Group, namely, the Pentecost Sandstone, Elgee Siltstone and Yampi Formation and intrusive igneous rocks. By its location it might be expected that the base rocks of the Montgomery Reef complex would belong in this series.

The Islands

The low Montgomery Islands at the centre of the main reef (Fig.1) consist of Quaternary sediments comprising mud banks and sand sheets (Brooke 1995). They are a product of marine sedimentary processes since inundation.

The five rocky High Clifty Islands comprise Paleoproterozoic rocks mapped (Map Sheet SD51-16 & 15) as possibly Pentecost Sandstone, one of the uppermost members of the Kimberley Group. However, archaeologist Sue O'Connor (1987) noted the presence at Ngalanguru Island of both "quartz sandstone and limestone". Brooke (1995) noted that these islands have "cliffed and etched limestone shorelines formed in flat bedded massive stromatolitic limestone and siltstone". During a WAMSI visit to Montgomery Reef (September 2009) landings were made on three of the five High Clifty Islands and the following observations were made.

On top of all the High Clifty Islands there is a cap of blocky, bedded, strongly jointed, fine-grained quartz sandstone or siltstone, that is the basis for mapping the islands as Pentecost Sandstone (Fig. 5). The sandstones overlie beds of a massive, silicified, laminated, richly stromatolitic dolomite that outcrops along the island shores and is the rock referred to by O'Connor and Brooke as limestone. This rock is very hard and very heavy and breaks into sharp edges. It was used for tool-making by the pre-contact inhabitants. It appears to be an unnamed formation and is not mentioned in the geological notes accompanying the map sheet. Some layers of the stromatolite domes exposed at the surface have a hard covering of secondary accretion that is stark white and, from a distance, makes the rocks look as if they are covered with cormorant droppings (Figs 6, 7). On the shore, below high tide mark, the dolomite is grey and etched (*i.e.* eroded into multi-faceted, sharp-edged ridges and turrets). On the eastern shores of the islands the top of the dolomite is up to 14 m above low tide level. In places it is horizontally laminated and gently folded and there is a 3–4° dip to the northwest so that, while it forms supralittoral cliffs along the eastern shores, on most islands it disappears into the intertidal zone along the western or northwestern shores.

Wuljarli and Egret Islands

These islands are located on the upper level of the reef flat at the south eastern side of the main Montgomery Reef platform, a step up from the lower level close to the reef front (Figs 3, 4). Like the High Clifty Islands, Wuljarli and Egret Islands are mapped as Pentecost Sandstone. Landings were made on all three islands and the rocks of them all were found to be blocky fine-grained quartzite like the upper rocks of the High Clifty Islands. On the southwestern shore of Wuljarlu Island there is also a southwest-dipping conglomerate comprising rounded river stones in a ferrous matrix. There was no dolomite on any of these islands.



Figure 3. The Egret Islands on the edge of the high platform on the south-eastern margin of Montgomery Reef. Note the double containment banks of the high platform margin above the lower platform, with sand fans along their downside margin, and the crescent-shaped pools formed by coalescing ridges of rhodoliths and coral rubble in the lagoon. (Data courtesy of WAMSI and Airborne Research Australia, and images processed by Curtin University.)

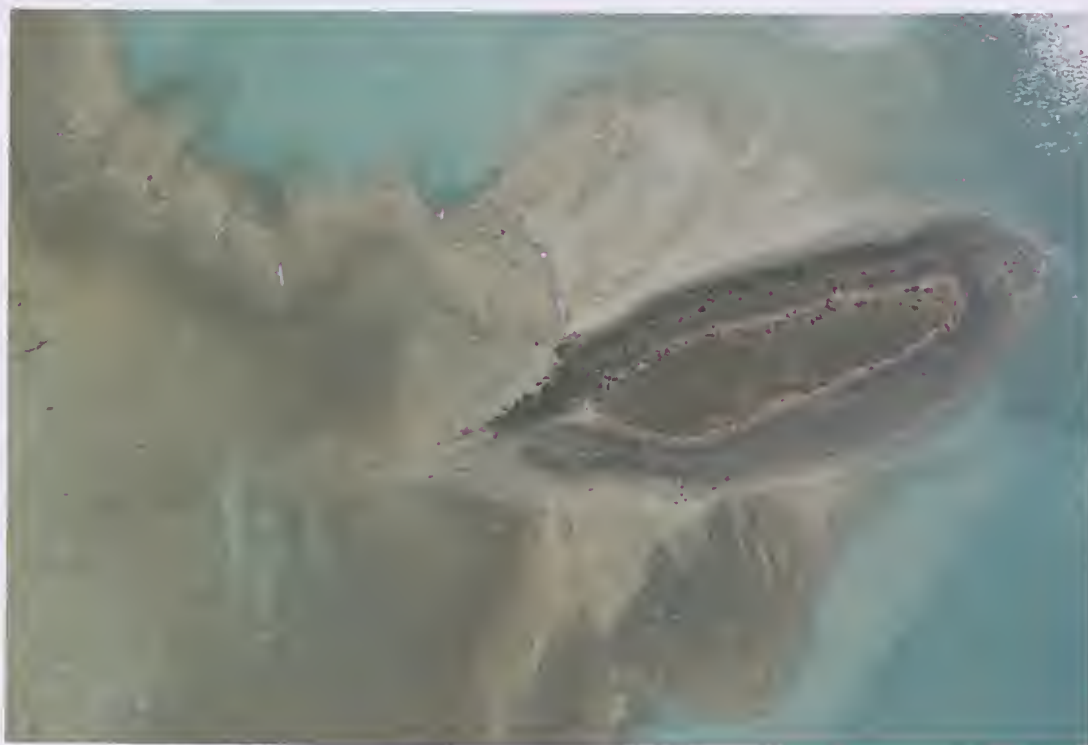


Figure 4. Wulajarlu Isand on the rim of the upper lagoon of Montgomery Reef where it impinges on the reef-front without a lower reef flat. This island is built of Paleoproterozoic quartz sand stone and conglomerates and there is no dolomite. (Data courtesy of WAMSI and Airborne Research Australia, and image processed by Curtin University.)



Figure 5. On the top of Wulajarlu Island, looking north at high tide. Blocky quartz sandstone in the foreground, the Egret Islands on the skyline. (Photo Barry Wilson).

Montgomery Reef and the High Clifty Reef

While the rocks of the eastern islands are Paleoproterozoic and probably of the Kimberley Group, there is no published account of the rock of the reef platforms, *i.e.* beneath the Holocene sediment and crustose algal veneer. In September 2009, a WAMSI party landed on the eastern margin of the main Montgomery Reef opposite High Clifty Reef during a period of neap low tide. Standing on the mid-littoral platform behind the reef crest, about two hundred metres from the reef edge, there is a group of massive, silicified dolomite rocks, the tops of which are emergent at high tide (Fig. 9). Stromatolite structures were not observed in these rocks but the lithology of the rock is otherwise quite similar to the stromatolitic dolomite of the High Clifty Islands. One flat-topped stack about 10 m in diameter, stands 4 m high above the lower reef flat surface, its upper part demarcated from the etched lower part by a conspicuous bedding plane with a slight dip west. These rocks were thought to be *in situ* erosional relics of the rock platform. If that is the case, the lower, mid-littoral rock platform on this part of the main Montgomery Reef has a base of massive dolomite that is older than the Pentecost Sandstone which, on the High Clifty Islands, overlies it. However, the thickness of the Holocene sedimentary veneer on the reef surface around the emergent stacks is unknown.

Intertidal habitats of the Montgomery Reef complex

The following notes provide a provisional account of the habitats of Montgomery Reef. They are derived

mainly from reports by Brooke (1995, 1997), interpretation of high definition imagery produced by Curtin University for WAMSI, field surveys by W.A. Museum and AIMS, and the recent field observations by the authors.

High Clifty Reef

Brooke (1997) noted some shoreline features around Ngalanguru Island. Wells *et al.* (1995) referred to "gentle terracing" of the reef platform and noted the presence of a large lagoon. Aerial photographs (Fig. 2) show a wide reef flat and lagoon on the western side of the High Clifty Islands. The western reef edge, bordering the High Clifty channel, appears to be poorly defined and observations by the WAMSI party during a period of neap tides indicated that this reef platform is lower than that of Montgomery Reef on the opposite side of the channel. The eastern side of High Clifty Reef has a steep fore-reef slope but the reef edge was not observed.

The Breakwater

The Breakwater is a long finger of reef jutting north from the western end of the main Montgomery Reef (Fig. 1). It appears to be a distinct structure attached to the main reef. Brooke (1997) provided a description of a site on the western side, noting that the lower-littoral ramp is characterized by extensive algal turf and pavement with two to three low terraces around 20 cm high. Reef-front coral growth did not feature in his description except for *Porites* sp. rimming shallow sandy pools. The mid-littoral reef flat is composed of a network of pools separated by



Figure 6. Top of the stromatolite dolomite forming a supra-littoral bench on a small islet south of Ngalanguru Island, High Clifty Group. Note the circular tops of large stromatolites in the foreground and the stark white crust over much of the rock surface. This surface appears to be the top of the dolomite sequence exposed by removal of the sandstone above it. (Photo Barry Wilson.)



Figure 7. Two forms of stromatolite, about 3 m above high tide level on the northern side of a small islet south of Ngalanguru Island, High Clifty Group. (Photo Barry Wilson.)

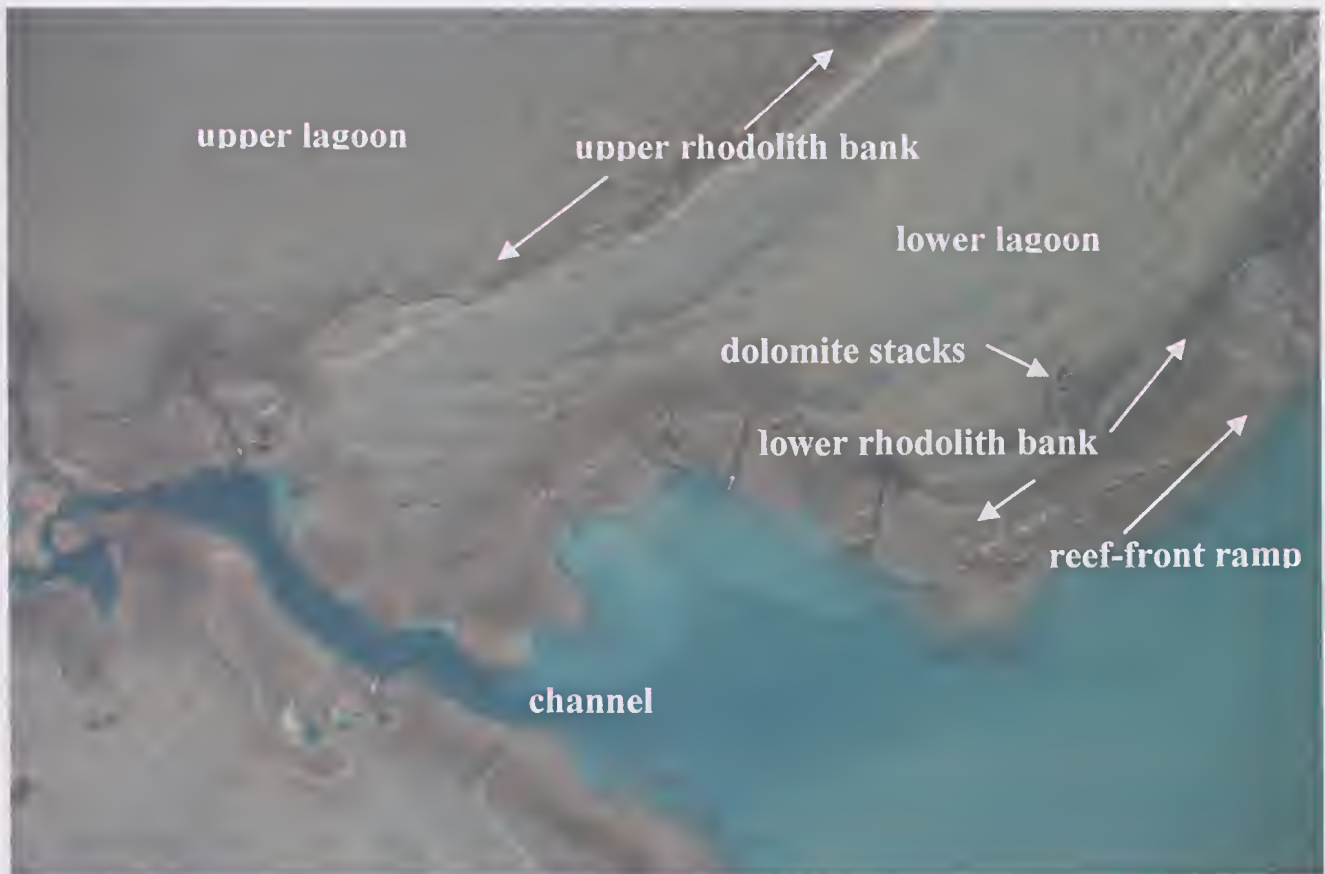


Figure 8. The south-eastern margin of Montgomery Reef, opposite High Clifty Reef. Note the broad reef-front ramp dissected at intervals by drainage gutters, and the reef crest with rhodolith banks impounding shallow pools on the midlittoral reef flat with pools. Running diagonally across the top left corner is the higher complex of rhodolith banks that impound the high lagoon. A major drainage channel entering from the left originates in the high lagoon. (Data courtesy of WAMSI and Airborne Research Australia, and image processed by Curtin University.)

narrow strips of algal pavement. These clear water pools also contain abundant coarse sand and calcareous mud.

Main Montgomery Reef

a) The subtidal fore-reef

The subtidal fore-reef zone is difficult to observe. The following notes derive from drop-camera and ROV observations made by AIMS (Andrew Heyward *pers. com.*). Around most of the reef's periphery the fore-reef is a vertical, stepped or steeply sloping wall to a depth of about 10 m and thence a slope to the surrounding seabed at around 20 m. The wall appears to bear little epifaunal or epiphytic growth. There are sand sheets in the sublittoral zone at some localities, often with pronounced "dune" formation, probably a result of the intense tidal currents [up to 2 m/sec associated with an 11m tidal range during Spring Tides, S.Blake *pers. obs*] recorded around the margins of Montgomery Reef. A fore-reef spur and groove system is not present. Nor is there a rich community of large *Porites* sp. and foliaceous corals like those known to occur in this zone of those few Kimberley fringing reefs that have been studied. However, there are many shallow subtidal ledges and patch reefs that bear moderately diverse coral communities. The seabed beyond the fore-reef is a rocky pavement with little sediment and bears well developed though patchy filter-

feeding communities of mainly sponges, sea-whips, sea-fans and soft corals.

b) Lower-littoral – reef-front ramp

The lower-littoral reef-front of Montgomery is a high-energy environment, not from wave action but from intense off-reef tidal flow. It is an extreme habitat where calcareous algae and low turf algae flourish but coral colonies are small and sparse. The huge volume of water impounded above the two impoundments banks and the many lesser terraces on the reef flat, results in spectacular, high velocity cascades over the terraces where the reef-front is high and steep and, in spring tide periods, over the reef front (Fig. 10). At such times, the larger drainage channels across the lower reef platform act like mountain rivers with extremely turbulent flow.

The reef-front ramp around Montgomery Reef is clearly evident in aerial photographs as a prominent zone varying in width from 50 to 100 m. It is generally high and steep, sloping at around 5–10° or more, sometimes convex, and has a distinct reef edge. At Spring Low Tide the reef edge may be several meters above water level (Figure 10). The ramp pavement is covered with a calcareous algal crust and a low turf. In most places the ramp is distinctly terraced by ridges of crustose algae a few cm high that impound networks of shallow pools, rather like a miniature Javanese hillside with rice



Figure 9. A massive dolomite stack on the mid-littoral reef flat near the south-eastern margin of Montgomery Reef (15°55.221'S; 124°18.795'E). Etched rocks on the lower part (*i.e.* below high tide level). Also visible as a cluster of small dots on Figure 8. (Photo Steve Blake, WAMSI.)



Figure 10. The reef edge at low tide; major channel, south west of Wulajarlu Island, Montgomery Reef. (Image courtesy Tim Willings, Pearl Sea Coastal Cruises)

terraces. The depth of the algal crust is unknown but is probably superficial.

Corals in the reef-front zone may be common, sparse or lacking. When present, corals are small colonies with flattened morphologies, mostly growing around the edges of the shallow pools. There is no zone of prolific coral growth along the reef-front like that of fringing reefs in the Bonaparte Archipelago and no evidence of a

Holocene coralline limestone wedge and outward reef growth at the reef-front.

c) Mid-littoral – reef crest

A boulder zone is lacking but commonly there is a reef crest equivalent comprising an elevated bank of rhodoliths up to 100 m wide fronted by a narrow fan of coarse sand (Figs 11, 12, 13). Unlike the boulders of coral

reef crests that are derived from the fore-reef and deposited by wave action, the rhodoliths appear to be derived from the sandy pools of the mid-littoral lagoon behind the reef crest and deposited there by ebbing tidal flow and wind-driven waves. The rhodolith banks are mobile, moved back and forth over the reef crest zone by tidal flow. They are generally very long and wind their way around the reef crest zone, often dividing into multiple bands that coalesce. The rhodolith banks are not terraces in the strict sense but they impound water behind and between them. The rhodoliths are irregular in form. Some have a core of coral fragments but many are more or less globular, ranging in diameter from 5 cm to 12 cm and are of entirely algal construction (Fig. 13).

d) Mid-littoral reef flat

The reef flat of Montgomery Reef, behind the reef crest, is unusually high in the intertidal zone and, at least on the eastern side, is formed at two distinct levels that are separated by an upper rhodolith impoundment bank (Figs 8, 11).

(i) Lower reef flat

The lower mid-littoral reef flat behind the reef crest varies in its nature, sometimes being a typical reef flat with an exposed pavement, crustose surface and low algal turf, and sometimes comprising a mosaic of shallow, knee-deep to waist-deep (at low tide) pools separated by secondary rhodolith ridges or crustose coralline algal ridges, the tops of which may be exposed. Aerial photographs show that the ridges are crescent-shaped and coalescent (Figs 3, 8) with steep outer margins and sloping inner margins, indicating that they are formed by the force of the ebb tide. In areas where pools dominate, this habitat might be called a lower mid-

littoral lagoon rather than a reef flat, but neither term is strictly apt.

The pools are lenticular, with sand, rhodolith and rubble beds and contain moderately diverse coral communities, leafy brown algae and some seagrass (*Thalassia*). Similar configurations of rhodolith ridges and pools were observed at Turtle Reef in the nearby Talbot Bay on Yampi Peninsula (Wilson *et al.*, this volume, Fig. 9). The abundant rhodoliths apparently grow in the pools where they are rolled by the tide to form the networks of ridges and eventually up onto the reef crest where they build the banks that rim and impound the pools and lagoon.

(ii) Upper reef flat (lagoon)

The upper reef flat is actually a shallow lagoon occupying most of the area of Montgomery Reef although there are some areas of rock pavement exposed at low tide. Little information is available at this time on the extent of coral and rhodolith growth in this zone. Aerial photographs show that the high lagoon includes areas where shallow, lenticular pools dominate, separated by coalescing ridges of rhodoliths and rubble, like those of the lower reef flat/lagoon so that vigorous rhodolith growth may be inferred.

The upper and lower platforms are demarcated by the upper complex of rhodolith banks, with a sand fan in front of it (Fig. 3). This upper terrace is virtually continuous and almost encircles Montgomery Reef and is clearly evident in the satellite images and the aerial photographs (Figures 1, 3, 11). Its height is not known. This conspicuous feature may be related to the underlying geological structure or a historical constructional feature relating to a Holocene (eustatic)

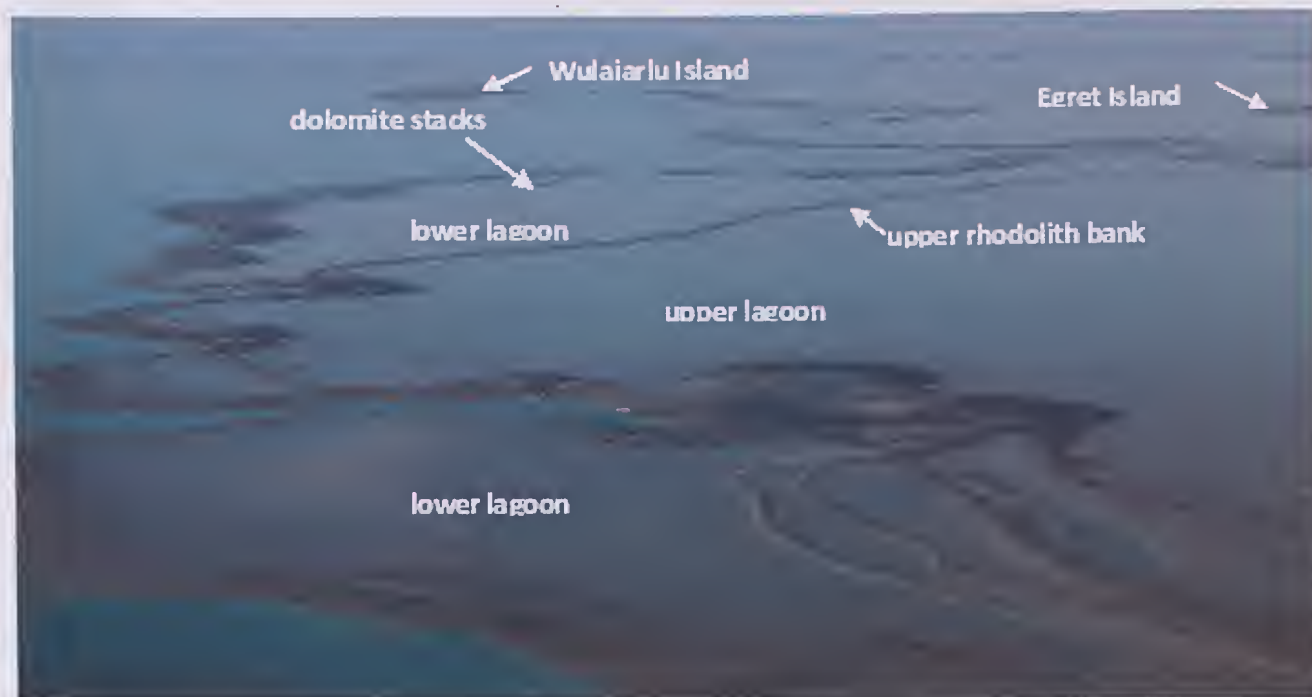


Figure 11: Rhodolith banks, lagoons and reef-front ramps along the S.E margin of Montgomery Reef. In the right fore-ground there are several rhodolith banks forming steps down from the upper lagoon to a mid-littoral reef flat. In the centre a tongue of the upper lagoon stretches to the reef edge and there is no mid-littoral reef flat. Wulajarlul Island top left; Eeret Island top right margin. (Photo Steve Blake, WAMSI)



Figure 12. Rhodolith bank on the reef crest; S.E. Montgomery Reef ($15^{\circ}55.331'E$; $124^{\circ}18.851'E$; elevation c. 4 m). Mid-littoral reef flat on the left; High Clifly Reef and islands in the background. (Photo Barry Wilson.)



Figure 13. Rhodoliths on the reef crest (see Fig. 12). Some of these have a coral fragment core but the majority are entirely of algal construction. (Photo Barry Wilson.)

high sea level. However, it is more likely to be a contemporary constructional, biogenic feature relating to tidal level.

The area occupied by the upper reef flat lagoon is enormous (c. 350 km²). It forms a vast light trap at low tide, with shallow conditions where autotrophic organisms flourish without exposure to the air or significant wave action (except during cyclonic storms). Primary productivity in these intertidal lagoons has not yet been measured but must be prodigious.

Summary and discussion

Reef growth

While there is a diverse coral fauna on Montgomery Reef, there is no prolific coral growth on the reef-front edge or the fore-reef wall and no evidence of the development of a reef-front biogenic limestone wedge. In other words, there is little reef-building activity in the reef-front zone and no significant lateral reef growth. However, there is vigorous biological growth of both rhodoliths and scleractinian corals in the pools and lagoons of the intertidal platform behind the rhodolith impoundment banks. Biogenic rubble and sand produced by these processes is filling in the pools and lagoons and raising the level of the platform.

The rhodolith banks cover large areas of the reef crest, pools and lagoons of the reef flat and clearly play a significant reef-building role. It would be interesting to obtain estimates of the rates of growth of the rhodoliths and corals but the impression gained from visual observations is that the rhodoliths are the primary reef-building organism on the Montgomery Reef platform.

The presence and configuration of these ridges and banks of rhodoliths and algal terraces, and the pools and lagoons they create, are functions of the macro-tidal regime and an unusual biogeomorphic feature. Kuenen (1933) discussed the importance of "lithothamnium" in reef-building on coral reefs and mentioned a report of the Siboga Expedition (Weber 1902) of "lithothamnium in loose nodules covering bare reefs ... in several parts of the East Indies". This latter study has not been seen but is the only reference known to these authors to large scale intertidal rhodolith banks and significant reef-building by these organisms.

It is suggested that calcareous algae may be the predominant reef-building organisms on Montgomery Reef, probably more significant than the corals, affecting the process in two ways:

- by their own carbonate production in the shallow pools and lagoons of the reef platform, and
- by their construction of the rhodolith banks and terraces around the perimeter of the reef that create the lagoonal habitat where the bulk of the carbonate production takes place (by rhodoliths and corals).

The vast area (c. 350 km²) of shallow, sheltered, sunlit, lagoon and pools of the Montgomery Reef platform represents a very significant extent of Benthic Primary Production Habitat. High primary production in the impounded lagoons may be the explanation of the

abundance of herbivorous macrofauna, notably green turtles and dugong, for which this area is renowned. If this is true, the rhodolith banks may be responsible for it.

Age of the islands

In the mainland area adjacent to Montgomery Reef, the second youngest unit in the Kimberley Group series is the Pentecost Sandstone and it is underlain by the Elgee Siltstone. Both these units are older than 1790±4 Ma, based on zircon dating of the intrusive Hart Dolerite (Schmidt and Williams 2008). Assuming that the quartz sandstone of Wuljarli and the Egret Islands and atop the High Clifty Islands is correctly mapped as Pentecost Sandstone, the rocks of those islands are Paleoproterozoic and around 1.8 billion years old.

Identity and age of the High Clifty stromatolites

Commonly, along the eastern shores of the High Clifty Islands, the top of the dolomite bed is exposed as a supratidal bench around 12–14 m above low tide level. In those situations the stromatolites are exposed on the surface as well preserved dome-shaped bosses, up to 1 m in diameter (Fig. 6). On worn, flat surfaces, they appear as finely laminated concentric rings. Where the stromatolites are exposed in section on cliff faces, they appear as cone-shaped structures with irregular, drooping layers at the top (Fig. 7). At one location a cluster of massive stromatolites was observed comprising rounded turrets standing up to 30 cm high, and occupying an area of around 20 m² (Fig. 7).

The High Clifty stromatolites were first reported by Mr Kevin Coates who took specimens to Dr Kathleen Grey of the Western Australian Geological Survey in the late 1980s. Dr Grey identified them as a previously unknown form of conical stromatolites belonging to the Group (morpho-genus) *Conophyton*. She has confirmed that specimens collected by the WAMSI party in September 2009 are of the same kind (Grey *pers. com.*). These stromatolites are unlike any Form (morpho-species) known from the Kimberley area. *Conophyton* usually indicates quiet water conditions, below the wave base and the High Clifty examples represent a biohermic construction in the Kimberley Basin very early in the history of life on this planet.

At the time of this report, the High Clifty stromatolites remain undescribed and their stratigraphic interpretation is uncertain. The Group *Conophyton* is common throughout the Proterozoic. It ranges into the Cambrian and there are modern analogues, so the age of the succession cannot be determined until the taxon can be identified to Form level although stratigraphically a Paleoproterozoic age is indicated.

In regard to the age and stratigraphic relationships of the stromatolitic dolomite, and noting that on the High Clifty Islands it underlies the quartz sandstone mapped as Pentecost Sandstone, Dr Grey (*pers. com.*) suggested three possible interpretations:

- It is a hitherto unknown carbonate unit within the Pentecost Sandstone.
- It is a previously unrecognized facies within the older Elgee Siltstone.

- The stromatolite unit and overlying sandstone of the High Clifty Islands are not part of the Kimberley Group, but are either a younger or older sedimentary package that has not yet been recognized elsewhere in the Kimberley.

Age of the rocks of Montgomery Reef platform

If the dolomite stacks of the lower platform at the eastern end of the main Montgomery Reef are correctly correlated with the stromatolitic dolomite of the High Clifty Islands, it may be assumed that the rock of the lower platform in that area is also of Paleoproterozoic age. The age of the rocks of the upper platform remains conjectural. Because they are higher than the dolomite of the lower platform it is possible that they are Pentecost Sandstone, like the Wuljarli and Egret Islands.

The age of the contemporary biogenic limestone that veneers the Proterozoic rocks of the reef platform surface is certainly Holocene. It is possible that there is Pleistocene coralline limestone beneath the Holocene veneer but no surface exposure of it was seen on Montgomery Reef (or anywhere else in the Kimberley north of Cape Leveque). There is evidence of ongoing subsidence of the continental margin in the Kimberley (Gregory 1913; Teichert and Fairbridge 1948; Fairbridge 1953; Carrigy and Fairbridge 1964; Jongsma 1970; Sandiford 2007) in which case Pleistocene reef limestone, if it exists, is likely to be at some depth below the Montgomery Reef platform surface.

Age and formation of the reef platform

While the base rocks of the Montgomery Reef structure are probably of early Proterozoic age, the means and the time at which the flat reef platform was created are conjectural. There are several possibilities.

1. A wave-cut rock platform

Edwards (1958) described wave-cut rock platforms around the shores of islands in the Buccaneer Archipelago and the mainland of the Yampi Peninsula. He noted that such rock platforms are best developed where the shore rocks are quartz-feldspar porphyry or schists that weather easily and poorly developed where the rocks are quartzites. The rock exposures of the islands of Montgomery Reef are all hard quartzites or silicified dolomite and there are no wave-cut rock platforms around their shores. It is improbable that the intertidal platform of Montgomery Reef could be an erosional surface created by wave action and chemical erosion during the Holocene.

2. A Quaternary coral reef platform built on and around a Proterozoic rock core.

Such a process would require extremely rapid reef growth to create a platform reef as large as Montgomery. It could be possible if there were a pre-existing Late Pleistocene reef (as at Ningaloo Reef) upon which Holocene reef growth occurred. However, the evidence of subsidence in the region suggests that this is unlikely. Also, if there were rapid contemporary reef growth, vigorous reef-front and fore-reef coral communities would be expected. This does not appear to be the case. Those habitats are poorly populated by corals and there is no evidence of lateral reef growth. Upward growth on

the reef platform would level and raise the surface but would not create a reef platform on the scale of Montgomery Reef without there being lateral growth as well.

3. A pre-existing flat terrestrial erosional surface

Prior to the post-Last Glacial Maxima transgression, the Montgomery structure would have stood as a mountain on a plain many kilometres from the coast. The rocks of which it is built are probably upper units of the Kimberley Group. In this regard, Montgomery Reef is like the fringing reefs of the Kimberley Bioregion where Holocene biogenic growth appears to be built directly on Proterozoic rocks of the Kimberley Group, except that at Montgomery there is no evidence of a Holocene biogenic limestone wedge at the reef-front.

We suggest that, prior to the Last Glacial Maxima, the Montgomery structure was a flat-topped terrestrial mesa. There are analogues of such structures, of that age and of similar height and area, further inland in the Kimberley Basin in a similar position in relation to the boundary between the basin and the King Leopold Orogen (e.g. Mount House, Mount Clifton). The primary geomorphic features of Montgomery Reef today are the same as those of the inland mesas – flat top, vertical walls, peripheral canyon-like incisions. By this interpretation, the main geomorphic features of Montgomery Reef, including its flat top, have been inherited from its long history of terrestrial erosion.

Conversion of the terrestrial Montgomery mesa to a marine platform reef would have occurred in the Holocene with the advent of the post-Last Glacial Maxima transgression. Mean Sea Level rose to just above the flat top of what was previously the mesa, placing it within the intertidal zone of a macro-tidal shore, open to colonization by intertidal marine organisms. Geomorphic features of the reef surface today (central mud islands, sand sheets, lagoons and rhodolith banks) are results of contemporary marine coral and algal reef-building processes superimposed on pre-existing terrestrial features, perhaps further leveling the intertidal platform surface by means of biogenic growth and sedimentation.

Conclusions

Montgomery Reef is not a coral platform reef in the strict sense. It is a coral reef in the ecological sense of having diverse coral growth in the lagoons and pools of the intertidal platform but its geomorphic form is atypical. There is no evidence of lateral reef growth and it does not have a biogenic limestone framework. Rather, the evidence suggests that it is an inundated terrestrial structure, built of Paleoproterozoic metasedimentary rocks, with a Holocene veneer of biogenic limestone and sediment on its intertidal platform surface. The thickness of the Holocene veneer is unknown but is probably not great. A drilling program on the reef flat would be required to confirm this interpretation.

The reef has inherited its primary geomorphic features, including its level platform, from its terrestrial erosional history. Contemporary geomorphic processes on the reef platform are constructional and involve production and distribution of modern biogenic

sediments. Extreme macro-tidal conditions and wind-driven waves are the dominant forces involved and the formation of vast mobile banks of rhodoliths that impound shallow lagoons is the key factor that creates the highly unusual intertidal habitats of the reef platform.

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Kimberley beach and barrier systems: An overview

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Abstract

The 4340 km long Kimberley coast is dominated by usually steep rocky shores, which occupy over 80% of the open coast. It also contains extensive areas of mangroves particularly in embayments and 1360 generally sandy beaches, which occupy 713 km (16%) of the more exposed open coast. Because of the high tide ranges (3–11 m) and generally low short waves ($H_b = 0.1$ m, $T = 3$ –5 sec) most beaches have a relative tide range > 10 and consequently are predominately tide-dominated (71%), with 25% fronted by coral and rock flats, 3% tide-modified and only 1% wave-dominated. Beach location and length is controlled by the geology, with most bounded by rock headlands and backed by rocky slopes and with an average length of only 0.5 km. Only 31% of the beaches are backed by some form of barrier development. In these low regressive barriers dominate with 264 consisting of beach ridges, 35 backed by usually low stable foredunes, while usually minor dune transgression backs only 70 beaches.

Keywords: Kimberley coast, beach, beach types, barriers, dunes

Introduction

The Kimberley coast borders the rugged Kimberley Plateau and extends from the Dampier Peninsula in the west to Cambridge Gulf in the east. It has a predominately rugged, bedrock-dominated highly irregular shoreline that consists of over 4000 km of more open coast, with a total shoreline length of over 13 000 km, much of the shoreline in crenulate sheltered inlets. This paper is concerned with the more open shoreline, which is exposed for the most part to ocean waves together with the meso- to mega-tides of the region. While the coast is bedrock dominated, it is potentially rich in sediments derived from both terrigenous and biological sources. Where suitable these sediments have been deposited in 1360 generally small beach systems (Table 1), with only 32% backed by some form of barrier development, usually low beach ridges and foredunes, with only 70 beaches backed by transgressive dunes. The beach and dune systems provide a different morphology to the bordering rocky terrain and as a consequence a very important habitat for both turtles and crocodiles and for a wide range of flora and fauna.

The Kimberley beaches are a product of the available sediments, the usually low waves, high tides and generally light to moderate winds, all set in a tropical-monsoonal climate. The beaches are physically constrained by the bordering bedrock headlands, islands, islets and reefs, while many are also fronted by fringing coral reefs. As such they represent a suite of beach-barrier systems, with both similarities to other northern Australian tropical beaches, yet distinctive in the controls exerted by both the bedrock, which results in short embayed beaches with lower waves; and the high tides which result in predominately tide-dominated beaches.

This paper presents an overview of all 1360 Kimberley beach and barrier systems located between Broome and the Western Australian–Northern Territory border.

Geology and bedrock control

The geology of the Kimberley region is dominated by the Kimberley Basin, bordered to the west by parts of the Canning Basin and King Leopold Orogen, and to the east by the Bonaparte Basin. Beginning in the west, the Canning Basin is characterized by deeply weathered shallow marine sediments, blanketed by longitudinal dunes. It forms the low lying Dampier Peninsula which at the coast is characterised by scarped red bluffs exposing the pindan soil, and low rocky headlands, including the red sandstone cliffs of Cape Leveque. The Canning Basin underlies King Sound and is bordered on the east by a narrow band of heavily folded rocks of the King Leopold Oregon, which forms the rugged terrain between the eastern entrance to King Sound and Walcott Sound and extends west to include the islands of the Buccaneer Archipelago.

Table 1

Northern Australia beach-coast characteristics. Modified from Short 2006b.

	Number beaches	Sandy coast (km)	Total coast (km)	Sandy %	Mean beach length (km)
Kimberley	1360	702	4340	16	0.52
Northern Territory	1488	1902	5029	18	1.28
Cape York	641	1509	2501	60	2.35
Northern Australia	3489	4114	11 869	35	1.17



Figure 1. Faint Point in the western Kimberley is composed of Proterozoic sandstone. This view shows the joint-controlled bedrock ridges and typifies the over-riding role of bedrock along the Kimberley coast (A D Short).

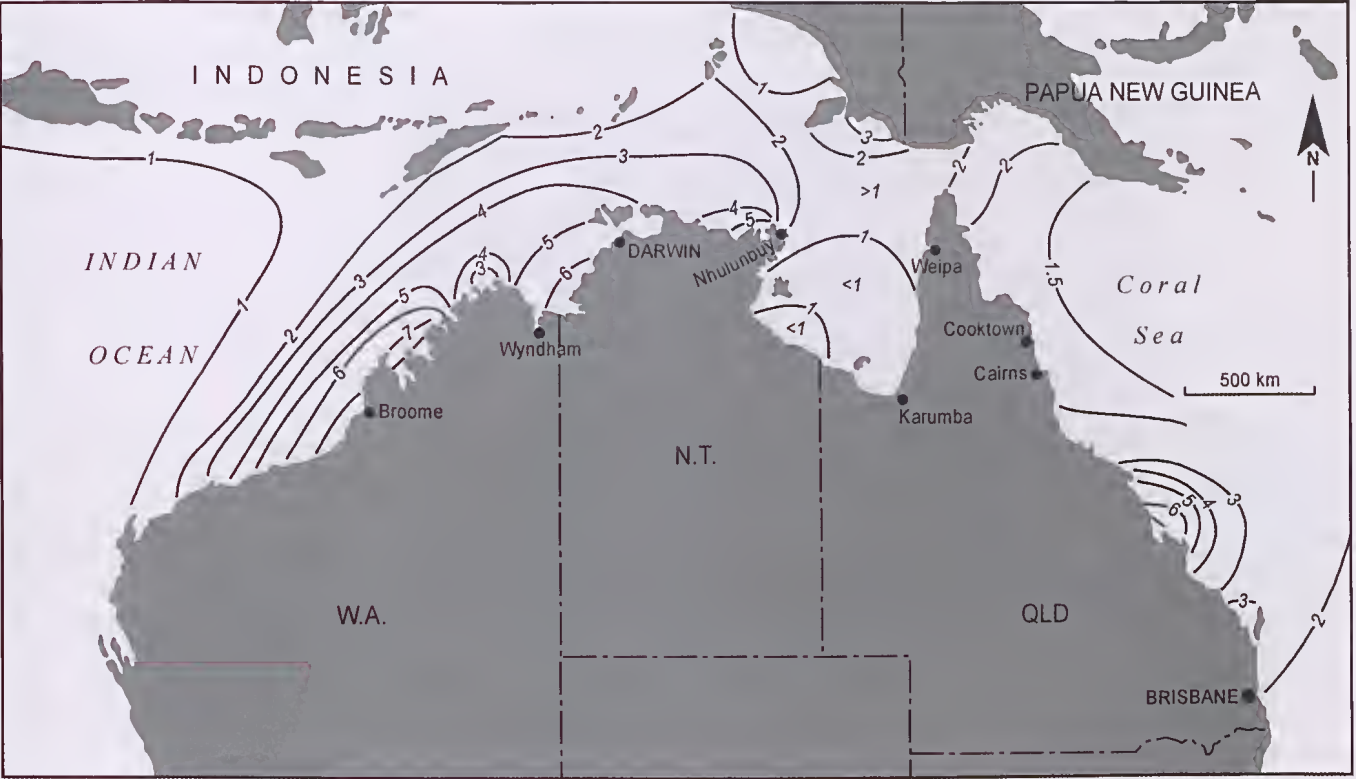
The Kimberley Basin forms most of the Kimberley shoreline and consists of two dominant units. Horizontally bedded sedimentary rocks form the core of the basin, and while dating between 1800 to 1650 Ma they have experienced only minor faulting and warping. The sandstones are capped and replaced in places by extensive basalt deposits that date to 1800 Ma. Both units have however been uplifted and subjected to deep weathering and erosion along joint lines that trend roughly 10° (NNE-SSW) and 280° (WNW-ESE). As a consequence, all creeks and rivers parallel these joints in places for 10's of kilometer, such as the Prince Regent River. The jointing control is also prominent along the coast forming many elongate joint-aligned inlets and valleys (Fig. 1). At the coast the plateau forms often steep cliffs a few tens of metres high but ranging up to nearly 200 m in height in the north at sandstone Cape Torrens (183 m), and basalt Clifty Point (186 m) and Crystal Head (191 m). Most of the coast and cliffs are however dominated by sandstone with the basalt more prevalent in the interior like the Mitchell Plateau, and only dominating along parts of the northern coast around Port Warrender, Cape Bougainville and east of Cape Londonderry.

Cambridge Gulf marks the abrupt boundary between the rugged sandstone coast and the low-lying sediments of the Bonaparte Basin, which occupy the eastern shores of the gulf. The low sandstone Cape Domett marks the eastern entrance to the gulf, with the shore extending 75 km east to the Northern Territory border at Pelican

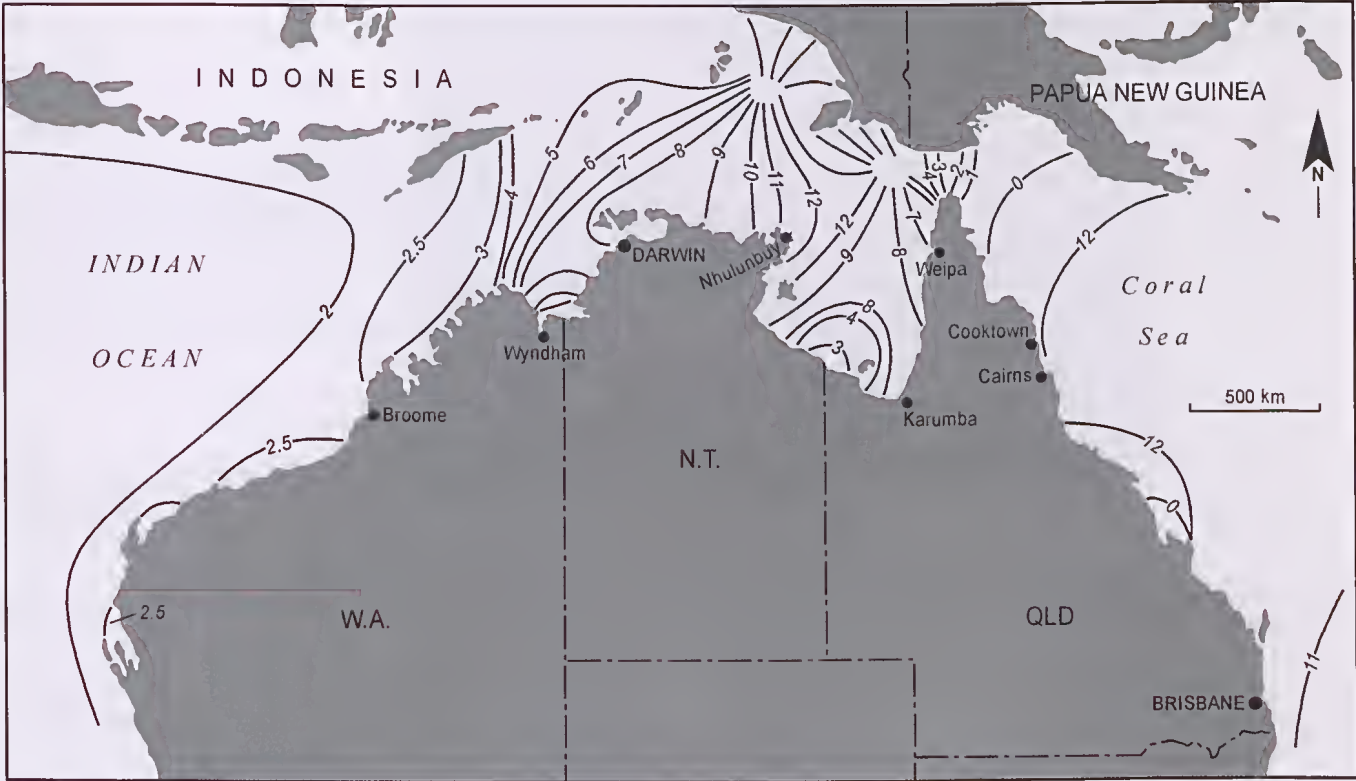
Island. The final 30 km consists of a series of low barrier islands that extend to border, and then beyond to the extensive tidal flats of the Victoria River delta.

Coastal processes

The Kimberley coast is dominated by its by meso- to mega-tide ranges (Fig. 2). Spring tides reach 10 m at Broome, 11 m at Derby, 9 m at Hall Point and 8 m at Wyndham, with the lowest spring ranges being 3 m at Napier Broome Bay and Lesueur Island. The Kimberley coast has the third highest tide range in the world and the highest in Australia. In contrast, waves are predominately low short (3–5 sec) wind waves (Fig. 3), which are further lowered through wave refraction and attenuation into the bays and across the shallow inshore (Short 2010b). As a consequence, 50% of the beaches receive waves averaging only 10 cm, 30% 20 cm waves, 10% 30 cm, while the maximum average wave height of 1 m reaches less than 1% of beaches. The wind regime is low to moderate in velocity and seasonally bi-directional. The moderate velocity winter southeast trades blow offshore along much of the coast, with lighter onshore northwesterly winds accompanying the summer wet season. Only occasional tropical cyclones produce extreme conditions with strong winds, rain, storm seas, flooding and storm surges. However, because of their low spatial and temporal frequency they do not impact the modal coastal conditions. They can, however,



Co-range



Co-tidal range

Figure 2. Co-range and co-tidal lines for the northern Australian coast. In the Kimberley spring tides range from 3 to 11 m, while the co-tide lines show the west to east propagation of the tide wave. Source: Short, 2006b.

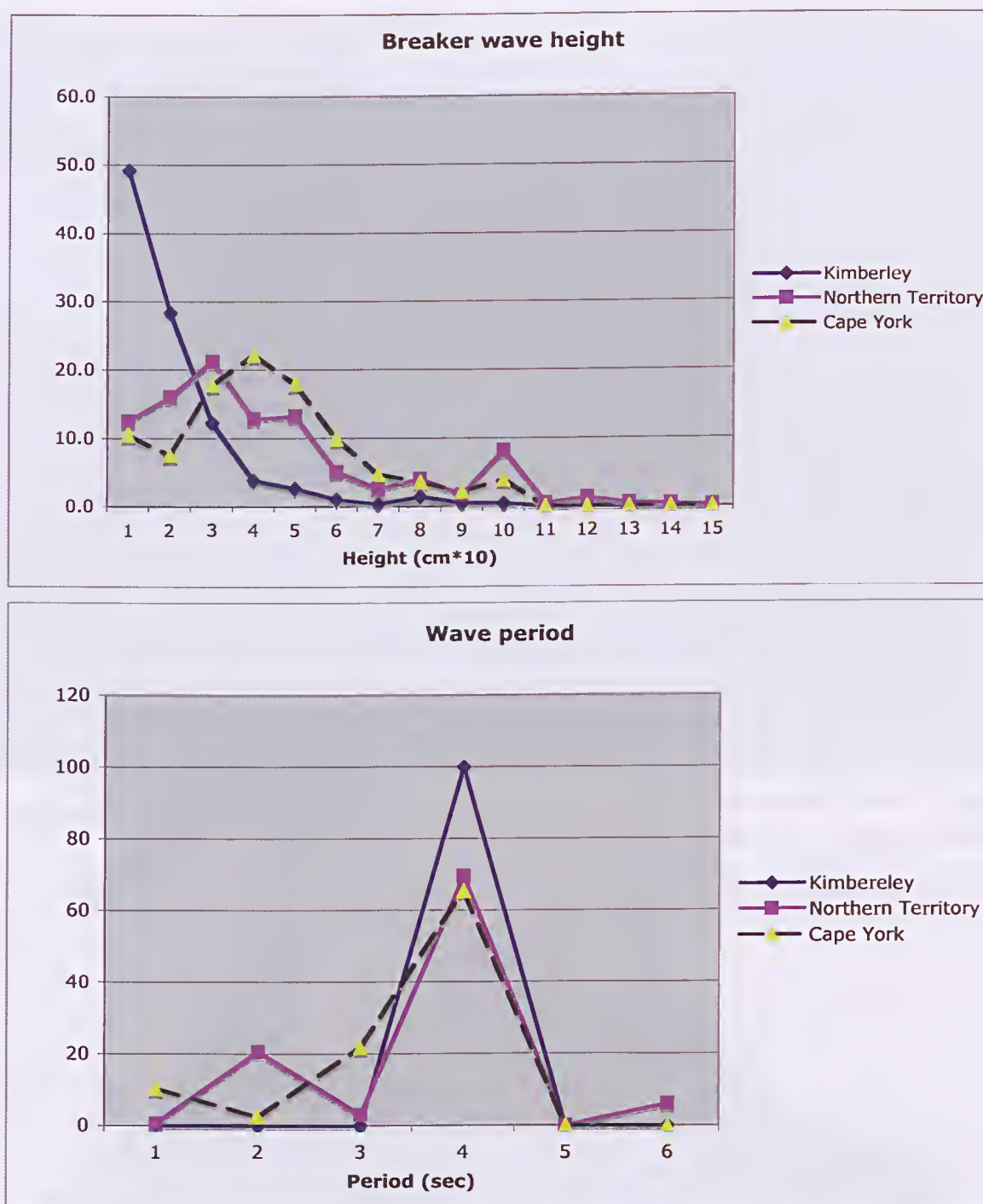


Figure 3. Breaker wave height and period across northern Australia. The Kimberley region has the lowest waves averaging 0.1 m, and typical short period, a product of the short seas and protection afforded most Kimberley beaches.

overwash the low beaches and beach ridges and leave storm deposits in suitable locations (Nott 2006). The coast can therefore be classified as tide-dominated, with only a few sections of more east-facing coast receiving enough onshore wind and accompanying wave energy to be classified as tide-modified to wave-dominated.

Methodology

This paper reports on the results of a long-term project to study all Kimberley beach and barrier systems (Short

2006b). The author first visited the Kimberley in 1980 as part of a University of Sydney team that undertook an intensive study of wave-tide-beach process on Cable Beach, Broome. The site was selected because of its high tide range, yet moderate wave activity (Wright *et al.* 1982a, b). Fieldwork for this project was undertaken by vehicle to the Dampier Peninsula in 1992, by plane to photograph every beach in 1997, and by small boat to facilitate beach landings between Wyndham and Broome in 2001. Additional information was sourced from large-scale maps (1:50 000 and 1:100 000), aerial photographs and Google images of the entire coast.

Beach systems

Beach systems can be classified based on their breaker wave height (H_b), wave period (T), sediment size or fall velocity (W_s) and tide range (TR). The relative tide range

$RTR = TR/H_b$

is used to delineate between waved-dominated ($RTR<3$), tide-modified ($RTR\ 3-10$) and tide-dominated ($RTR > 10$) beach types (Short 2006a). Within each beach type the dimensionless fall velocity (Ω)

$\Omega = H_b/T\ W_s$

is used to classify beach states between the dissipative ($\Omega>6$) to reflective ($\Omega<1$) end of each beach type, resulting in six wave-dominated, three tide-modified and four tide-dominated beach states around the Australian coast. In addition, some high tide beaches are fronted by either intertidal coral reef or rock flats and comprise a separate type, bringing the total to four beach types with fifteen beach states (Short 2006a; Short & Woodroffe 2009).

Table 2 provides the mean breaker wave height, tide range and RTR for all northern Australian beaches (Broome to Cooktown). Note the overall low breaker wave height and average meso- to macro-tides, and resulting range in RTR. The wave-dominated beaches have an $RTR<4$, the tide-modified between 3 and 9, and the tide-dominated between 7 and 28, in general agreement with Short (2006a).

Barrier/dune systems

Beaches are commonly backed by longer-term deposits called barriers, the sediments comprising the barrier derived from the beach or former active beaches. Barriers can be grouped into stable barriers which usually consist of a beach backed by a single stable beach ridge or foredune; regressive barriers where a positive sediment budget has resulted in shoreline progradation and the deposition of a series of beach and/or foredune

ridges; and transgressive barriers where the foredune has been destabilized and sand blown inland as transgressive dunes in the form of blowouts, parabolic dunes and transverse dunes. Barriers can range in size from very small systems a few tens of metres in dimensions to massive systems extending longshore and inshore for many kilometres (see Short and Woodroffe, 2009).

Kimberley beach systems

This section provides an overview of the Kimberley beach systems, followed by a review of the barrier systems that back 30% of the beaches. Full details of every one of the 1360 Kimberley beaches are provided by Short (2006b), while the barriers are incorporated in an overview of all Australian barrier systems in Short (2010a).

The 1360 beaches average only 0.52 km in length (standard deviation (σ) = 1.16 km), the longest at Cape Baskerville is 14 km long, followed by 12 km long Cable Beach. There are only four beaches greater than 10 km long, 62 greater than 2 km, 110 greater than 1 km, the remaining 1242 all 1 km or less in length, with eleven of these only 20 m in length.

The Kimberley coast has the shortest beaches and smallest barrier systems in Australia. This is a product of the short bedrock-controlled length of the beaches; their low wave energy which limits onshore sediment transport and deposition; and the generally low velocity and commonly offshore trade winds, which limit coastal dune development. The beaches can be classified into the four types, but with an overriding dominance of tide-dominated and to a lesser extent beaches fronted by coral reef or rock flats. Table 3 lists of the beach types and their states by number and length of coast they occupy. The only wave-dominated beaches are 14 reflective beaches located, two near Cape Leveque, a couple in the north, and ten reflective boulder beaches (Fig. 4) most

Table 2

Mean wave height, tide range and RTR associated with northern Australian beach types. Source: Short 2006b.

	Beach type ¹	H_b (m)	Tide Range (m)	RTR
Wave- dominated	1	0.55	2.15	4
	2	0.87	1.40	2
	3	1.33	1.40	1
Tide-modified	7	0.64	2.99	5
	8	0.90	2.44	3
	9	0.66	5.88	9
Tide-dominated	10	0.40	2.70	7
	11	0.28	4.02	14
	12	0.16	5.03	31
	13	0.16	4.54	28
Beach + rock flats	14	0.42	3.64	9
Beach+ reef flats	15	0.26	4.32	17

¹ see Table 3 for names of each beach state (1–15).

Table 3

Kimberley beach states by number and length of coast. Modified from Short 2006b.

No.	Beach state	Number	%	km	%
1	Reflective (R)	14	1.0	9.8	1.4
2	Low Tide Terrace (LTT)	0	0	0	0
3	Transverse bar & rip	0	0	0	0
4	Rhythmic bar & rip	0	0	0	0
5	Longshore bar & trough	0	0	0	0
6	Dissipative	0	0	0	0
7	R+LTT	21	1.5	20	2.8
8	R+LT rips	3	0.2	7.1	1.1
9	Ultra dissipative	22	1.6	78.2	11.1
10	R+sand ridges	25	1.8	12.8	1.8
11	R+sand flats	417	30.7	181.7	25.9
12	R+tidal flats (sand)	418	30.7	208.7	29.7
13	R+tidal flats (mud)	105	7.7	42.8	6.1
14	R+rock flats/platform	172	12.6	99.3	14.1
15	R+coral reef	163	12.0	41.8	6.0
Total		1360	100	702.2	100



Figure 4. Cobles and boulders form the beach near The Funnel (Collier Bay). It is composed of locally derived platey sandstone. Vegetation debris (left) marks the high tide limit (A D Short).



Figure 5. The beach at Cape Dussejour is fronted by 500 m wide ridged sand flats, similar in extent to those that front most Kimberley beaches (A D Short).

around Bare Hill on the western entrance to Cambridge Gulf. These are all characterized by a relatively steep high tide beach, with no inter- to sub-tidal platform.

Tide-modified beaches total only 46, with about half located on the more exposed Dampier Peninsula including Cable Beach, north of Broome, a few around the northern Curran Point, Cape Talbot and Berkeley River, and the remainder east of Cape Domett. The eastern Kimberley tide-modified beaches are all located in more exposed locations that receive higher wave generated by the southeast Trade winds or the summer northwesterly winds. Twenty one have steep high tide beaches fronted by low tide terraces, 22 are wide long gradient ultradissipative like Cable Beach, and just three, on the exposed Cape St Lambert beaches, have low tide rips. These are the only persistent beach rips in the Kimberley another indication of the low wave conditions.

Tide-dominated beaches dominate and occur right around the coast from Crab Creek, near Broome, in the east to Pelican Island in the west, and on 71% of the beaches in between. They grade from the slightly higher energy ridged sand flats (2% Fig. 5); with decreasing wave energy to those fronted by sand flats (31%); tidal sand flat (31%), and with 8% fronted by mud flats. In all cases they consist of a low energy usually coarse shell rich high tide beach, fronted by the intertidal flats. The 900 plus intertidal sand and/or mud flats range in width at from 10 m to 2.5 km, with a mean width of 250 m ($\sigma = 290$ m) (Fig. 5).

A substantial number of beaches (25%) consist of a high tide beach and fringing fringing coral reef (6%) or intertidal rock flats (14%). The fringing reefs (Fig. 6) are a product of the tropical climate, while the rock flats are another example of the overriding role played by bedrock and in some location beachrock in influencing beach morphology.

The Kimberley beach and dune sediments characteristics are provided in Table 4. Sediments located on the intertidal sand flats are the coarsest (0.9 mm) and highest in carbonate (61%). Size and percentage carbonate decrease slightly into the high tide swash zone (0.8 mm and 59%). The foredune and transgressive dunes have the finest sand (0.6 mm) though quite coarse for dune sand, and the lowest carbonate (51%). The sorting is the opposite of what would be expected, with the sand flats and swash moderately well sorted, though both with large standard deviations, while the dunes sand are poorly sorted, though with a smaller standard deviation. Both the coarseness and poorer sorting of the dune sand can probably be explained by the fact many of the dunes are low and prone to occasional wave overwashing that may deposit coarser shells in the finer matrix.

Another interesting features of the sediment characteristics is the predominance of carbonate sediments on a coast with an abundance of river supplied terrigenous sediments. The source for the carbonate sediments is the fringing coral reefs, sand flats and seagrass meadows, all located in shallow water close to



Figure 6. Fringing coral reefs fronting a series of beaches east of Cape Londonderry. The beaches are backed by sandstone bluffs (A D Short).

Table 4

Kimberley beach-dune sediment characteristics

Position	Sample number	Carbonate %	Carb. σ	Mean diam (mm)	Mean σ (mm)	Sorting σ	Sort. σ
Sand flats	132	61	33	0.9	0.33	0.76	1.14
Swash	247	59	33	0.8	0.36	0.90	1.11
Dune	117	51	33	0.6	0.2	1.51	0.57

the shore. The massive volumes of terrigenous sediment supplied to the coast by the rivers and creeks is generally deposited in low energy bays and gulfs, and unable to be supplied to the shore because of its embayed location and low wave energy. Major beaches and barrier deposits are only present at the mouths of the Drysdale, King George and Berkeley rivers, each containing high to very high proportions of river derived sands. Beauty Point on the western side of the Drysdale has 5 km wide series of five successive beach ridge barriers contain 90% river derived sands, together with intervening mangrove filled inter-barrier depressions; The King George has a series of multiple sandy beach ridges and recurved spits on the eastern side of its bedrock-controlled mouth which contain 99% terrigenous sands (Fig. 7); while down wind of the Berkeley at Cape St Lambert, is the most extensive transgressive sand dunes in the Kimberley and composed of 99% river-derived quartz sand.

Kimberley barrier systems

The Kimberley coast region has the fewest and smallest barrier systems in Australia (Short, 2010a). This is a result of a number of factors beginning with the dominance of low, short waves that are only capable of

transporting small amounts of sediment to the shore at low rates; second, is the wind regimes, with the strong trades blowing offshore on most beaches, with dunes only forming on some of the most exposed east-facing beaches; third is the generally coarse nature of the sediments which precludes their providing a source for coastal dunes; and finally is the steep bedrock coast which provides only limited accommodation space for beaches to form. Hence, while there is an abundance of terrigenous and carbonate sand available in the subtidal zone, most remains there with insufficient wave energy available to move it shoreward, and insufficient wind energy to produce substantial coastal dunes.

Barrier systems back 369 of the 1360 Kimberley beach systems, with the remaining 73% of the beaches of insufficient size to be termed a barrier, many backed by rocky slopes (Fig. 8). The barriers can be divided into three types: stable, regressive and transgressive (Table 5). Eight of the barriers consist of a stable boulder beach ridge (Fig. 4). There are 228 sandy beaches backed by a single beach ridge, while 28 consists of multiple beach ridges averaging seven ridges, but ranging from 2 to 40 ridges (Fig. 9). Ninety percent of the beaches and beach ridges (1227) are therefore solely wave deposited, with no backing aeolian dune deposits, most also fronted by the sand and tidal flats described above.

Aeolian activity resulting in the deposition of a foredune or transgressive dune on or in lee of the beaches and beach ridges backs only 105 of the beaches (8%). Most consist of a single usually low stable foredune (32) (Fig. 10). Only seven have regressive foredune ridges, consisting of usually 2 to 4 ridges (Fig. 11), with one system at Cape Talbot having 15 ridges. Sixty-nine beaches are backed by transgressive dunes, of which 40 have limited dune activity, while 29 have moderate to major dune activity, the most extensive extending 1–2 km inland around Red Bluff on the Dampier Peninsula (Fig.



Figure 7. The bedrock controlled mouth of the King George River with a series of sandy beach ridges extending to the east. The sediments for the ridges have been derived from the sandy river mouth shoals (A D Short).



Figure 8. A narrow high tide beach at Sanderson Point is backed by sandstone bluffs and fronted by intertidal beachrock. It illustrates the overriding role of bedrock in controlling beach and barrier morphodynamics (A D Short).

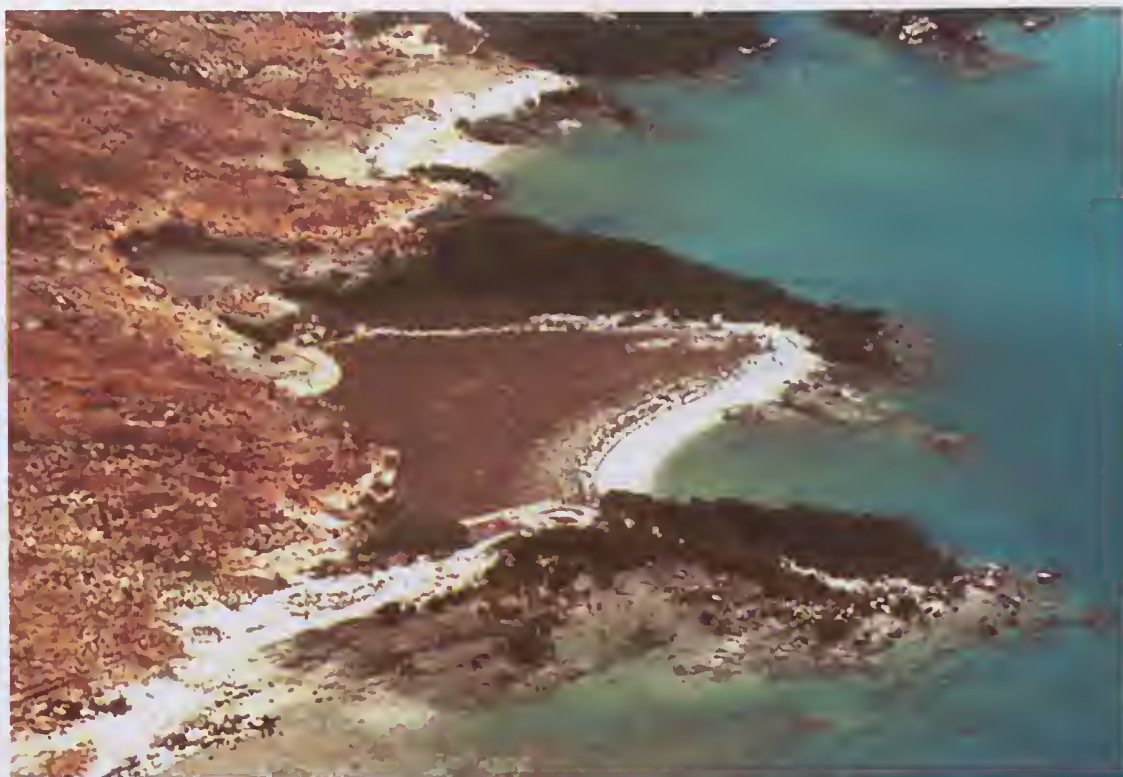


Figure 9. A small grassy rock and mangrove-bound beach ridge plain near Truscott. The 300 m wide plain contains multiple small, low beach ridges (A D Short)



Figure 10. A solitary foredune is squeezed in between beach and backing bedrock slopes at a beach near Gibson Point (A D Short).



Figure 11. A series of foredune ridges back this beach east of The Needles near the Northern Territory border (A D Short).



Figure 12. Transgressive dunes have extend up to 800 m inland either side of the Dampier Peninsula’s Coulomb Point (A D Short).

Table 5

Kimberley barrier types and number

	No barrier	Beach ridge	Foredune	Minor transgression	Mod-major transgression	Total
No barrier	991	–	–	–	–	991
Boulder	–	8	–	–	–	8
Stable	–	228	32	–	–	260
Regressive	–	28	4	–	–	32
Transgressive	–	–	–	40	29	69
Total	–	1255	36	40	29	1360

12), and 0.5–1 km inland around Cape St Lambert. All of the more active dune are located either on the Dampier Peninsula (33) or on section of the more easterly facing east Kimberley shore, particularly around the Berkeley River mouth (29), with only seven in between.

Summary and Discussion

The Kimberley coast has a bedrock-dominated shoreline. The several large river and numerous smaller rivers and creeks tend to flow into deeply embayed joint-controlled valleys depositing their terrigenous sediment well inland from the open coast where extensive tidal flats and mangrove forests dominate the depositional shores. Only three rivers – the Drysdale, King George and Berkeley have significant wave deposited beaches adjacent to their mouths, the beaches composed of river-derived sediments.

The 1360 Kimberley beach systems occupy only 16% of the 4333 km long open coast, with the remainder of the coast dominated by bedrock. The beaches remain

largely bedrock-controlled with an average length of only 520 m, the smallest in Australia. Further the beaches are predominately low energy tide-dominated systems. The typical beach is backed and bounded by bedrock slopes, has a single beach ridge and is fronted by sandy tidal flats averaging 250 m in width. Overall the combination of low wind waves and high tide ranges provide predominately tide-dominated beaches (63.5%), with only 15.3% tide modified and only one wave-dominated beach state (reflective) occurring on only 14 more exposed beaches. In addition, coral reefs fringed 12% while 13% are fronted by intertidal rock flats, the latter also a result of the bedrock dominance.

The barrier systems reflect the low level of wave and wind energy, as well as the generally coarser beach sediments. Most beaches abut backing bedrock and have no barrier. On the 360 barrier systems, most are single beach ridges (228) or foredune ridge (32), with a few regressive beach ridge (28) and foredune ridge (4) plains, again confirming the lack of available sediment. Regressive barriers capped by active dune transgression only occur on 69 barrier, 40 of which experience only

Table 6

Characteristics of Kimberley and Australian barrier systems (modified from Short, 2010a)

	Coast length km	Barrier length km	Number barriers #	total barrier area km ²	unstable area km ²	unstable %	barrier volume km ³	barrier mean vol m ³ /m	Holocene rate supply m ³ /m/yr
Kimberley	4333	456	368	223	66	17.8	1.0	2205	0.4
Australia	30671	12175	2476	23455	2765	11.7	281	22662	3.6

minor transgression, with the most extensive dunes extending up to 1 km inland and all located either on the more exposed Dampier Peninsula or east facing sections of the East Kimberley coast.

Table 6 summarises information on the Kimberley barriers. While the coast represents 14% of the Australian open coast the barriers contribute only 4% of Australian barriers by length of coast, 1.5% by number and 0.5% by volume. With a total Kimberley barrier area of 223 km², just over 80% are vegetated and stable the remainder experiencing either dune and/or overwash instability. The barriers have a mean volume of 2205 m³/m, the smallest in Australia, and have been supplied with sediment at an average rate of 0.4 m³/m/yr, again the lowest rate in Australia.

Whilst the Kimberley beaches and barriers are a secondary component of the coastal geomorphology, they do provide very important sites for landing and habitats for people and the native flora and fauna. The author observed turtle fin prints on almost every beach that was landed on, even on coarse cobble beaches, suggesting many beaches provide a nesting site for the turtles. Fresh crocodile foot prints were also a common sight on many beaches, again indicating they are used for resting and sunbaking. The beaches also provide the only easy landing for small boats at high tide and thereby access on an otherwise usually rugged coast. The beach ridges and dunes also offer a habitat for a range of coastal dune plants including coastal grasses *Spinifex longifolius*, *Ipomoea brasiliensis*, *Salsola kali*, *Fimbristylis cymosa*, *Fimbristylis sericea*, *Cyperus bulbosus* on the beach ridges, incipient foredune and foredune. Low shrubs *Acacia bivenosa*, *Lysiphyllum cunninghamii*, *Canavalia rosea*, *Triodia pungens* cover the larger foredunes; with dense shrub community of diverse plants, including some *Pandanus spiralis* grow on the hind dune and hollows, which then grade into pindan or rocky vegetation.

Conclusion

The Kimberley coast is a bedrock-dominated and controlled coast located in a humid monsoonal environment, with seasonal rainfall and several large river delivering substantial amounts of terrigenous

sediment to the coast. Most of this sediment is deposited in drowned river valleys and the subtidal, with little available for onshore deposition by waves. Wave energy is low and tides are high resulting in a predominance of tide-dominated beaches (64%), followed by beaches fronted by either reef or rock flats (20%), then tide-modified (14%).

The barrier systems, similarly, are few and reflect the dominance of tide-dominated systems, with most consisting of solitary beach or usually low foredune ridge (74%), while only 10% have experienced shoreline regression resulting in a few ridges. Limited transgressive dune activity in the form of coastal dunes occur on 16% of the barriers mainly on the most exposed Dampier Peninsula and parts of the east Kimberley coast.

The beaches and barriers are however an important component of the otherwise rocky open coast, providing sites for landing and turtle nesting, as well as a range for dune based ecosystems.

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Stratigraphic patterns in coastal sediment sequences in the Kimberley region, Western Australia: products of coastal form, oceanographic setting, sedimentary suites, sediment supply, and biogenesis

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Abstract

Coastal sediments in the Kimberley region occur in generally macrotidal environments with variable wave energy, reside in different coastal forms, and illustrate various styles of facies development and sedimentation leading to varying types of stratigraphic packages. The sedimentary patterns and stratigraphic patterns are determined by the coastal setting in terms of coastal morphology, oceanographic factors such as tide-dominated or wave-dominated prevailing conditions, or cyclone generated conditions, sediment delivery, and the dominance of gravel *versus* sand *versus* mud. The main stratigraphic packages range from gravel-dominated sequences and sand-dominated sequences, to shoaling sand-to-mud sequences to mud-dominated sequences, with local variations such as sequences with embedded sand lenses (buried spits/cheniers), and thin sediment sequences on rocky pavements. Bouldery shores, tempestites, sandy beaches, and sandy beach-ridge systems represent one extreme of the stratigraphic patterns, with gravel and sand dominated systems. King Sound and Cambridge Gulf represent an intermediate pattern, with sand-to-mud sequences, reflecting shoaling from low tidal to high tidal sedimentation. Port Warrender and the Lawley River Delta and local mud-filled embayments represent the other extreme of the patterns, with sediment sequences dominated by mud. In ria and embayment coastal settings, the most complex array of facies occur, representing the intricacy of sedimentation in sedimentologically diverse embayments; these include tidal-flat sediments, tidal creek sediments, sand underlying spits/cheniers, high-tidal alluvial fans, and beaches. Biogenesis can be a major factor in facies development, with effects ranging from mangrove-influenced sedimentation to fauna bioturbation and skeletal contribution.

Keywords: Kimberley Coast, tropical coast, coastal sediments, coastal stratigraphy

Introduction

The geographic coastal region of the Kimberley, encompassing the natural geomorphic coastal sectors of the Kimberley Coast, King Sound (including Stokes Bay), and Cambridge Gulf (Fig. 1), presents a globally unique ensemble of sedimentary packages set in a tropical (generally) macrotidal cyclone-influenced environment with variable wave energy (Brocx & Semeniuk 2011). These sedimentary packages range from shoaling sequences of tidal flat sediments, to beaches, prograded beach-ridge systems, tempestites, to bouldery shores. While shore boulder deposits comprise the most extensively developed sedimentary unit, and many other sediment suites, such as sandy beaches and spits, occur throughout the Kimberley region in site-specific areas such as coves and mouths of embayments, tidal flat sediments comprise the largest accumulations of sediments at any given site, occurring in the headwaters of large rias and embayments and in many of the smaller sheltered inlets and ravines. Prograded tidal flat sediments, as laterally extensive flats, form distinct coastal landforms, adding to the geomorphic character of the Kimberley region, and form the habitats for

mangroves and benthic tidal-flat fauna. In their various coastal settings, the other sedimentary suites, though volumetrically less significant site-specifically than tidal flat deposits, also form distinct coastal landforms, and add to the diversity of the coastal forms, sedimentary deposits, and habitats in the region.

To date, there have been a limited number of sedimentologic studies in the coastal zone of the Kimberley region; these include Gellatly (1970), Semeniuk (1981a, 1993), Lees (1992), Nott (2006), and Short (2006). Given the vastness of the area, understandably there have also been a limited number of studies that have involved stratigraphic analyses of the coastal sedimentary deposits of the Kimberley region. The main stratigraphic studies, to date, have been: Jennings & Coventry (1973) who investigated the spits in northern King Sound; Jennings (1975) who studied the relationship of tidal sediments to underlying red desert sand that comprise the linear dunes that adjoin the eastern shore of King Sound; Thom *et al.* (1975) who provided a stratigraphic cross-section of southern Cambridge Gulf across the tidal flats; Coleman & Wright (1978) who studied the sedimentation and stratigraphy from the alluvial plain to the tidal delta in Cambridge Gulf; Semeniuk (1980, 1981a, 1981b) who provided stratigraphic profiles of the tidal zone in King Sound,

relating them to modern sedimentary facies and earlier Holocene sequences; and Semeniuk (1983, 1985) who provided stratigraphic profiles of mangrove-vegetated coasts in the Mitchell River and Port Warrender area. Apart from Short (2006) who described the various sandy and pebbly beaches of the Kimberley region, relating them to waves, tides and their local coastal setting, there has been little published on coastal sediments of the Kimberley region that provides an integrated explanation of the variety of sediments types and the types of stratigraphic packages that they may develop.

This paper is a description of coastal sediments of the Kimberley region, their occurrences in relation to coastal setting, the processes leading to their development, the types of stratigraphic sequences generated along the various coasts, and a perspective of their significance globally. Details of sedimentary structures, sedimentary interrelationships, and the processes of sedimentation at the smaller and fine scales (*cf.*, Semeniuk 1981a) are beyond the scope of this paper and the objective is to provide a large scale view of the variety of sedimentary systems and stratigraphic packages that occur in the region and relate them to the main coastal processes and coastal settings.

The sedimentary environments and stratigraphic sites described in this paper are based on field work, involving boat-work, land-based vehicle, aerial surveys by fixed wing aircraft, and helicopter. Sampling sites are shown in Figure 1. All surveys were accompanied by documentary photography. Additional work was carried out by desktop aerial photographic studies. On-site studies involved describing coastal setting, determining stratigraphy by augering, coring, and from cliff exposures, and sampling of sediments from stratigraphic profiles and the sediment surface. Details of sampling Quaternary stratigraphy and sediments are provided in Semeniuk (1980, 1981a, 1983, 1985).

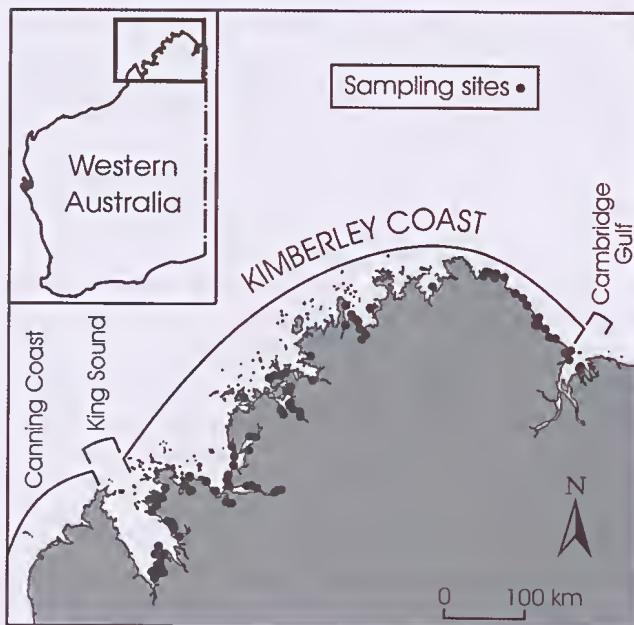


Figure 1. Location map showing King Sound, the Kimberley Coast, and Cambridge Gulf. The climate setting of the region is adapted from Gentilli (1972), and location of sampling sites.

Definition and limits to the Kimberley Coast and the Kimberley region

In this paper, the region of the Kimberley, is divided into three natural coastal units, following Semeniuk (1993) (Fig. 1):

1. the Kimberley Coast,
2. King Sound (including Stokes Bay), bordering the Kimberley Coast to the south-west, and
3. Cambridge Gulf, bordering the Kimberley Coast to the east.

The Kimberley Coast is the sector of ria shores cut into the Precambrian massif of the Kimberley Basin and King Leopold Orogen that (onshore) forms the Kimberley Plateau of (mainly) sandstone and (some) basalt. The Kimberley Coast (*sensu* Semeniuk 1993) is a rugged, dominantly rocky coastline with local sedimentary accumulations. Its geomorphic structure is dominated by medium and short rivers that have incised deep valleys into the sandstone and basalt regional plateau. As described in Brocx & Semeniuk (2011), the geological grain, faults, and boundary between geological units, such as between the Precambrian rock massif and Phanerozoic rocks, have been selectively eroded to form major valley tracts of the Fitzroy, May, and Meda Rivers and the Pentecost, Durack, and King Rivers. The southern to south-eastern margins of the Precambrian massif also have been incised by short rivers that form north-deriving tributaries to these larger rivers. The complex of larger rivers form the large gulfs, partly filled with sediments, *i.e.*, King Sound, Stokes Bay, and Cambridge Gulf. These rivers and their tributaries have delivered voluminous sediment to the gulfs from their respective large drainage basins. The short rivers, with smaller drainage basins, that incise and radially rim the Precambrian rock massif along its south-western, western, northern, north-eastern coastal margin, form the architecture of the ria shores of the Kimberley Coast.

King Sound (including Stokes Bay) and Cambridge Gulf are large funnel-shaped gulfs whose southern parts are composed of tide-dominated deltas of the Fitzroy River, and the combined May and Meda Rivers, and (for Cambridge Gulf) the combined contribution of the Pentecost, Durack, and King Rivers. King Sound is located between Dampier Peninsula (composed of Mesozoic rock overlain by Quaternary linear dunes), and to the north by folded rocks of the Precambrian King Leopold Orogen and north-east by a field of Quaternary linear dunes. From the south, it is dissected into two subsidiary gulfs (King Sound proper, and Stokes Bay) by a peninsula of Mesozoic rock that is mantled by Quaternary dunes. Cambridge Gulf is bordered by the rocks of the Kimberley Basin to the west, by Phanerozoic rocks to the east, and by faulted and folded Precambrian rocks of the Halls Creek Orogen to the south. As large embayments, King Sound and Cambridge Gulf have been carved out by the large rivers in the regions and, as such, are the depositional basins for the fluvially-derived sediments of these drainage basins. The sedimentary deposits are concentrated to the south within the gulfs, and the accumulations effectively are the deltaic deposits of the contributing rivers. Tidal processes have shaped these deposits into north-south oriented linear elongated

shoals, some of which are high-tidal emergent. As such, the deltas of the Fitzroy River, and the combined May and Meda Rivers, and for Cambridge Gulf the combined contribution of the Pentecost, Durack, and King Rivers are tide-dominated deltas.

Climate, oceanography, and coastal processes of the Kimberley region

The Kimberley geographic region is located in a tropical climate, with the coastal zone spanning several climate regions, *viz.*, following Gentili (1972), tropical subhumid in the Cambridge Gulf area, tropical humid centred on the Port Warrender area, tropical subhumid from Prince Regent River to northern King Sound, and tropical semi-arid in the King Sound area. The significance of the climate is that coastal rainfall influences local freshwater seepage, the extent that saline high-tidal flats are developed, and the development of beach rock, and evaporation determines the extent that saline high-tidal salt flats are developed. Wind in the region is variable regionally in direction and strength. It is instrumental in generating wind waves that affect shore processes, in mobilising sand into dunes, driving

landward migration of parabolic dunes, and in evaporation from the high-tidal salt flats.

The climate of the hinterland inland from the coast is also relevant in that rainfall in the drainage basins of the Kimberley Plateau determines the extent of run-off into the rivers which, in turn, determines the amount of freshwater and sediment delivered to the coast. Generally, the drainage basins of rivers and creeks that deliver freshwater and sediments to the coast are largely in a subhumid climate. Across the region, the variability in size of drainage basin, the lithologies where the drainage basin resides, and the rainfall result in variation of sediment volumes and particles types delivered to the coast. Quartz sandstone terrain yields quartz sand particle types, while felspathic quartz sandstone and interlayered sandstone and siltstone yield quartz sand and mud-sized particles, and basalt terrains and laterite-capped basalt terrains yield mud-dominated sediment.

The coastal zone of the Kimberley region is subject to four main oceanographic processes (Fig. 2): semi-diurnal tides, seasonally determined wind waves, prevailing swell, and seasonal and inter-annual cyclones. All these influence sedimentary processes but some are environmentally/geographically restricted and some, as

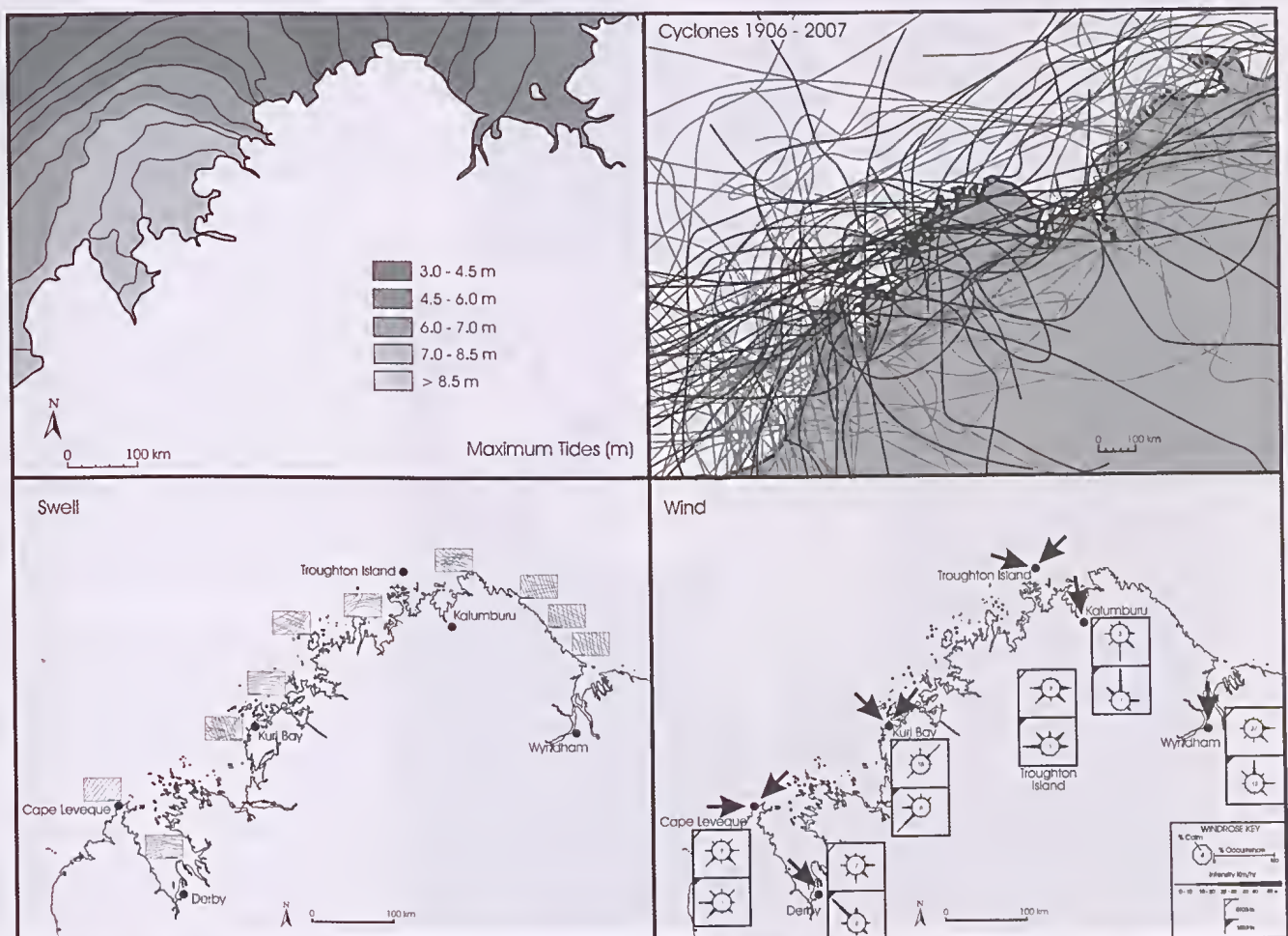


Figure 2. Swell patterns, wind, and wind wave directions, tide ranges, and cyclone paths in the Kimberley region. Swell patterns are shown for small representative sections of the coast. Wind roses are derived from the Bureau of Meteorology (2010) for the locations shown; the large arrows show the summarised directions for a given location, which will determine wind wave directions that will impinge on the coast.

noted, are seasonally specific. As such, they are variable in their coastal effects across the region. Additionally, the Kimberley Coast is highly indented and comprised of south-facing, west-facing, and north-facing inlets and embayments which, in many instances, are nearly wholly isolated from the open sea, being connected only by narrow channel-ways or waterways. While the latter are subject to inundation only by high tides, storm surges and cyclone-induced high-water, they are protected from the action of swell, wind waves, and storm waves.

The coast of the Kimberley region is macrotidal, with maximum tides ranging from 11.5 m in King Sound, to 10 m at Koolan Island, 8 m at Port Warrender, to 8 m at Cambridge Gulf, though tidal range decreases to mesotidal in the Berkeley River area. In fact, semi-diurnal large tides are a daily and pervasive dominant feature that affects the coast regardless of its geometry, degree of shelter, and orientation. Tidal waters and tidal currents are regionally pervasive even where tides penetrate into protected inlets and lagoons. As such, all portions of the coast from large open embayments to narrow secluded ravines, to tidal lagoons receive mud-bearing waters, and are subject to a varying degree to tidal currents. In particular, scour-lag and settling lag processes (see later) result in mud accumulating at the high tidal interval in embayments, lagoons, near-landlocked inlets/embayments, and where tidal waters can invade on high tides. In this paper, EHWS = equinoctial high water spring tide, MHWS = mean high water spring tide, MHWN = mean high water neap tide, MSL = mean sea level, MLWN = mean low water neap tide, MLWS = mean low water spring tide, and ELWS = equinoctial low water spring tide.

Oceanographically, the next important processes to affect sedimentation are wind waves and swell. Wind waves are pervasive even in areas sheltered from swell, but are more seasonal, reflecting the seasonality of wind patterns and, in particular, sea breezes. They are most effective in coastal processes where coasts are relatively exposed and, depending on fetch, they have variable effect on the coast. Although the sedimentologic effects of wind waves are region-wide, they have most influence on sedimentation where headlands and coves face wind directions, and where small islands act as foci for development of cusped forelands and tombolos. Swell is an all year phenomenon, deriving from northerly, north-westerly, north-easterly to south-westerly sectors, and impinges on exposed coasts facing these directions. Swell is refracted and dampened interacts with the shelving near-shore environment, and as it enters deeply embayed rias. However, swell is not a major wave form in the region.

Cyclones are inter-annual and seasonally determined phenomena (Lourensz 1981; Lough 1998), but highly localised in their effects on shore development. Cyclones result in elevated sea level, large waves, and storm surges. With cyclones there is winnowing of existing sedimentary deposits, transport and emplacement of sedimentary deposits above and well above the high tide mark, and coastal erosion. Cyclones also result in massive influx of freshwater into the coastal zone, and concomitant sediment delivery from rivers/creeks to the high-tidal alluvial fans.

Geology, landscape, rivers and valleys as architecture to the Kimberley coastal region, and ancestral topography and the coastal forms host to coastal sediments

Coastal forms in the Kimberley region have developed by marine inundation of onshore landforms and rivers, creeks, their tributaries and other valley tracts (Brocx & Semeniuk 2011), and by accumulation/erosion of Holocene sediments (Semeniuk 1981b). The main onshore landscape feature of the region is the Kimberley Plateau, a terrain underlain by rocks of the Kimberley Basin (mainly of fractured/faulted sandstone with some basalt). The Kimberley Plateau is deeply incised by rivers, creeks, and their tributaries forming trellis and dendritic drainage patterns as controlled by the geology. As a result, there are steep-sided ravines, with bluffs and cliffs, which at the coast result in steep rocky shores and cliffs, steep bouldery shores, narrow to open embayments, fracture-aligned gulfs, inlets, narrow ravines, archipelagos, and ocean-facing cliffs. The King Leopold Orogen, a tightly folded sequence of rock with fold axes oriented WNW, forms ridge-and-basin topography. Marine inundation of this topography has formed prominent WNW-striking peninsulae, inlets, linear embayments and lagoons, and chains of islands (as archipelago complexes), isolated or near-isolated linear high-tidal marine enclosures and, where fracture influences cross-oriented drainage, trellis-shaped embayments and inlets. Onshore ancestral topography thus directly determines coastal geomorphology in terms of size, shape, and orientation of embayments, and whether they have been fluvially derived, or are indented coasts, and if they grade into or are adjoined by an archipelago.

Following Brocx & Semeniuk (2011), there are eleven coastal forms in the Kimberley region that determine (or influence) the nature and style of sedimentary accumulations; these are (Fig. 3): 1. large funnel shaped gulfs; 2. large narrow v-shaped gulfs; 3. large broad embayments; 4. medium-sized to small narrow v-shaped ravines and valleys; 5. medium-sized to small embayments and coves; 6. isolated inlets and lagoons; 7. rectilinear to rhomboidal intersecting embayment/ inlet complexes; 8. archipelago-and-embayment complexes bordering the Kimberley Basin; 9. archipelago-and-inlet complexes bordering the King Leopold Orogen; 10. straight rocky shores; and 11. scattered islands in an archipelago.

Depending on the orientation and the oceanographic aspect of these coastal forms, there is a gradation of wave and tidal energy: coasts may be exposed to wind waves and prevailing swell and thus subject to the high energy of waves and tides; or relatively protected from prevailing wave action and subject mainly to tidal currents; or fully protected from wave action and only inundated on the highest tide at times of near slack-water and slack-water. The nature of the coast, how much of it is subject to waves and tidal currents, and how much sediment is delivered to or generated at the site will determine the style of sedimentary accumulation that will develop.

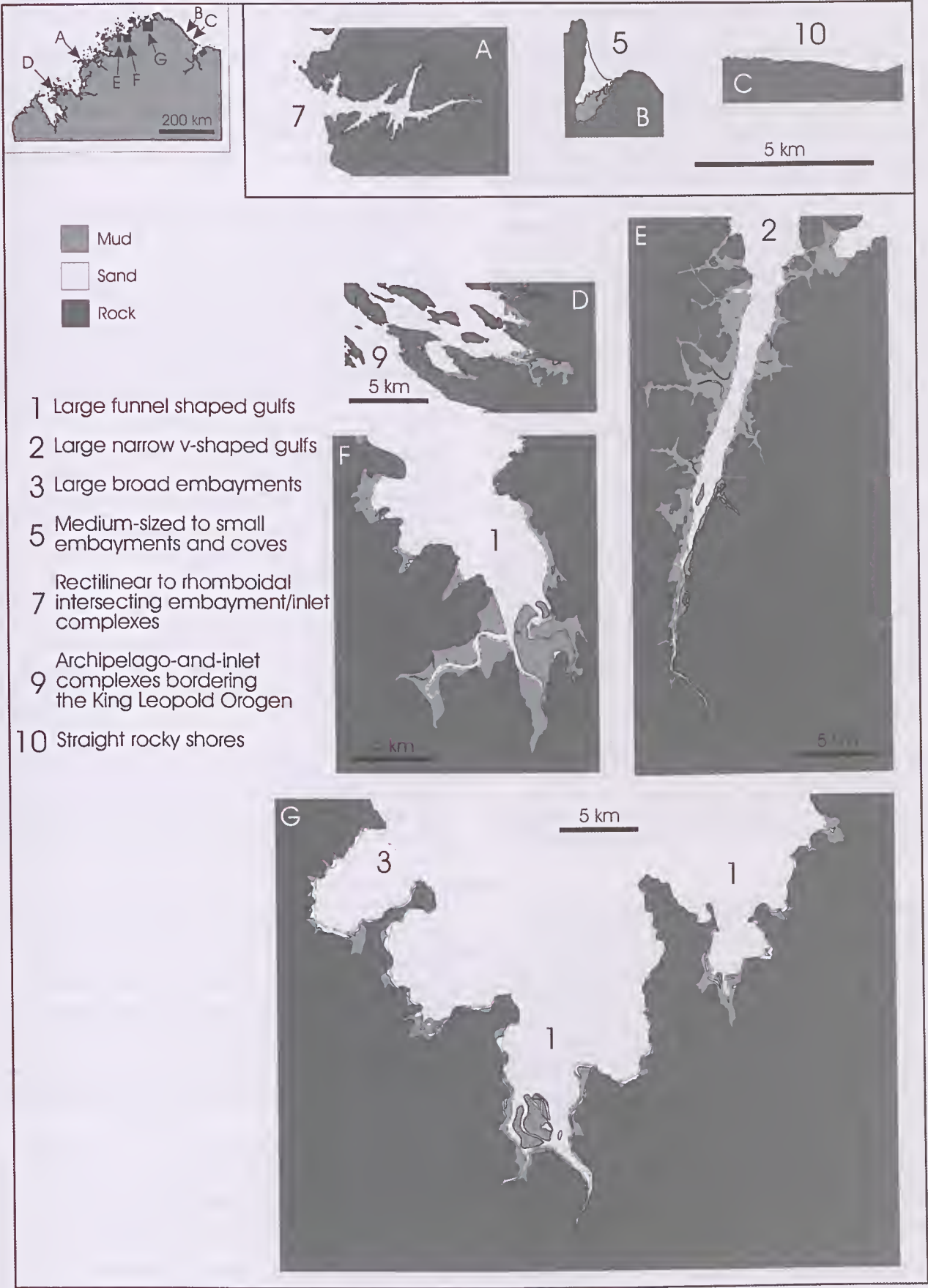


Figure 3. Coastal forms in the Kimberley region that determine (or influence) the nature and style of sedimentary accumulations (after Brocx & Semeniuk 2011). Bar scale for A, B, C, D, E, F & G is 5 km. The numbers refer to one of the eleven coastal forms mentioned in the text, and the letters A, B, C, etc. show the location of the example along the Kimberley Coast.

Processes of sedimentation

To provide a context of how sediment is transported to, along, and within the coastal zone, the main processes of sedimentation in the coastal zone, and those processes that result in sediment being delivered to the coastal zone, are briefly outlined here, drawing on local and international literature. The main processes of sedimentation that result in sediment accumulating in the coastal zone, from land to marine environment, are:

1. Long distance fluvial transport involving traction loads and suspension loads
2. Short distance fluvial transport involving traction loads and suspension loads
3. Sheet-wash on terrestrial slopes
4. Mass wasting along cliff lines contributing blocks, boulders, cobbles, and sand
5. Aeolian transport of drying high tidal sand on beaches to form dunes, and its further inland transport as parabolic dunes
6. Wave action driving sand and gravel shoreward
7. Storm surges driving sand, pebbles, and boulders shoreward
8. Longshore drift driven by oblique prevailing wave action or storm waves
9. Wind-driven currents mobilising suspended mud and sand alongshore and shorewards
10. Tidal currents that transport sand by traction and mud in suspension
11. Scour-lag and settling-lag resulting in mud accumulation in high-tidal zones
12. Biological activity (e.g., mangrove detritus, shell contribution)

These processes and their relevance to sedimentation in the coastal Kimberley region are described in Table 1

Sediment sources and styles of supply

Sediments in the Kimberley coastal zone are derived from six sources: 1. nearly *in situ* ancestral gravel and sand; 2. locally derived gravel and sand; 3. distally river-delivered derived sand, mud, and gravel; 4. reworked sediment from earlier Quaternary deposits and relict sediment; 5. biogenic sediment; and 6. locally derived intraclasts. These are described below in terms of sediment granulometry and composition, and in terms of the processes that deliver the sediments to the coast.

Gravel and sand, that is nearly *in situ*, contribute to the sediments in the coast zone. The rocky ranges, ridges, hills, slopes, and scree slopes of the Kimberley massif mainland are mantled with gravel and sand, and the valley tracts cut into the fracture-dominated Precambrian massif are floored with gravel and sand. These materials formed the ancestral topography and sediments and soils prior to the last post-glacial transgression. After the last glacial period, with sea level rising to its near-present position some 10,000–7000 years BP, the various materials mantling the ranges, ridges, hills, slopes, and valley tracts formed the sedimentary materials of the shore-lines. Those materials that were inundated and remained largely *in situ* formed boulder shores and sandy bouldery shores and gravelly shores. Those that were inundated and local reworked by waves, storm waves and cyclone-induced wave actions and surges, developed bouldery and gravelly shores, with rounded boulders and gravel, and bouldery shores showing imbricate structure. The extent that such deposits are *in situ* or reworked is dependant on the extent that the shore is sheltered from wave action. In many protected areas of the Kimberley ria shore and embayments, slopes and hill-sides subaerially covered in gravel scree descend directly into the tidal zone to form a steep bouldery shore. Where wave action is prevalent, the slopes and hill-sides subaerially covered in gravel scree descend directly into the tidal zone and the boulder and gravel deposits are reworked into mid to high-tidal ribbon

Table 1

Processes of sedimentation and their products

Process	Sedimentation products
Long distance fluvial transport	Long distance fluvial transport involving traction loads and suspension loads
Short distance fluvial transport	Short distance fluvial transport involving traction loads and suspension loads
Sheet-wash on slopes	Sheet-wash on terrestrial slopes
Mass wasting along cliff lines	Mass wasting along cliff lines contributing blocks, boulders, cobbles, sand
Aeolian transport of beaches to form dunes	Aeolian transport of drying high tidal sand on beaches to form dunes, and its further inland transport as parabolic dunes
Wave action driving sediment shoreward	Wave action driving sand and gravel shoreward
Storm surges driving sediment shoreward	Storm surges driving sand, pebbles, and boulders shoreward
Longshore drift	Longshore drift driven by oblique prevailing wave action or storm waves
Wind-driven currents mobilising sediment	Wind-driven currents mobilising suspended mud and sand alongshore and shorewards
Tidal currents transporting sediment	Tidal currents that transport sand by traction and mud in suspension
Scour-lag and settling-lag	Scour-lag and settling-lag resulting in mud accumulation in high-tidal zones (Postma 1961)
Biological activity	Biological activity (e.g., mangrove detritus, shell contribution)

deposits, becoming more rounded, and imbricated. The scree and the shore-line deposits are composed of large platy boulders. Where the shoreline rocks, particularly well-bedded sandstone and siltstone, have been fragmented by terrestrial erosion, salt weathering, and wave erosion to pebble-sized clasts, they form pebble shores along the rocky coasts, and can be transported to form pebble beaches, and pebble cheniers, tombolos, and barriers.

Locally derived gravel and sand is similar to that described above but has been transported to the shore by sheet-wash, mass wasting, or small creeks and rivulets active during the wet season. The latter deliver gravel and sand to rocky shores, to high-tidal deltas, or into ribbons of gravel and sand along the interface between the upland slopes and the tidal flat. Mass wasting along cliffs contributes blocks, boulders, and sand as chaotic masses, or as talus cones, both of which are reworked, transported and subject to rounding and attrition.

Sand, mud and gravel also are supplied by rivers. The medium sized and large rivers, such as the Fitzroy River, the Lawley River, the Prince Regent River, amongst others, have delivered, and continue to deliver much sedimentary material to the coastal environment. Thus, this sedimentary material has a distal origin. Because of the size of the drainage basins and the diversity of rock types at the source, some rivers deliver a diversity of particle types mineralogically and granulometrically. Quartz sandstones yield gravel and quartz sand, quartz/felspathic sandstones yield gravel, quartz sand and clays, basalt and lateritised basalt yield gravel and clays. Once delivered to the coast, wave action and tides partition the sediments into sand, muddy sand and mud lithofacies, and gravel.

In many locations of the Kimberley coastal region, there is erosion and remobilisation of pre-existing Quaternary sediments, including relict earlier Holocene sediment. Pre-existing Quaternary sediments and relict Holocene sediment include: 1. early to middle Holocene tidal mud formed under mangrove cover (with reworking, in the late Holocene to modern setting, of voluminous amounts of mud that is redistributed to mid-high tidal environments); 2. alluvial plains of the pre-transgression surface; 3. Pleistocene tidal flat deposits (these generate mud, quartz sand, and carbonate lithoclasts); 4. relict earlier Holocene sediment of shelly muddy sand, or muddy sand; and 5. Quaternary red sand dunes. The reworking of earlier deposits has resulted mainly in remobilisation and accumulation of mud and sand, with minor gravel. In some instances, the sediments are not remobilised, remaining in subtidal areas as relict sediment.

Biogenesis contributes sedimentary particles to and/or develops biogenic rock along the Kimberley coastal region. Biogenic materials include: 1. coral reefs along the shore zone; 2. calcareous algal reefs (biolithites, or boundstones) along the shore zone (Brocx & Semeniuk 2011); 3. calcareous algal encrustations on lithoclasts, shells, or corals to form rhodoliths; 4. coral fragments as gravel and coarse sand, derived from fringing coral reefs that border the low tidal zone of rocky shores, and transported shorewards by wave action along high energy coasts to form coral gravel deposits as spits,

cheniers, and beaches; 5. oyster and barnacle skeletons as gravel and coarse sand, derived from rocky shores, transported alongshore and shorewards by wave action along high energy coasts to form shell gravel deposits as spits, cheniers, and beaches; 6. benthic molluscs that inhabit tidal and subtidal sand and mud substrates, which remain *in situ* to contribute shell to the sediment, or are winnowed and transported alongshore and shorewards by wave action or tidal currents to contribute particles to the sand deposits; 7. benthic and epibiotic foraminifera of tidal and subtidal environments that contribute sand-sized skeletons, transported alongshore and shorewards by wave action or tidal currents to contribute particles to the sand deposits; 8. diatoms in tidal environments that contribute mud-sized skeletons, that are transported alongshore and shorewards to contribute particles to the mud deposits, or remain *in situ* in the local mud accumulations; 9. plant material as leaves (detritus), branches, logs, which break down and contribute to the organic-matter-rich muds, or to the development of pyrite-impregnated muds; and 10. plant material as *in situ* roots and trunks embedded in the mid to high-tidal mud deposits (Semeniuk 1980, 2008), which break down and contribute to the organic-matter-rich muds, and to the development of pyrite-impregnated muds. The range of biogenic skeletal particles in the sediments, as gravel to sand-sized grains derived from various extant biotopes, include: entire bivalves and their fragments, entire gastropods and their fragments, foraminifera tests and fragments, (encrusting) calcareous algal fragments, segments of articulated calcareous algae, rhodoliths, bryozoans, echinoderm test fragments and spines, coral gravel and sand-sized fragments, sponge spicules, barnacles and their fragments, and hydrozoans.

Cementation in the tidal zone of beaches develops beach rock (slope-parallel indurated beach sand, shelly sand, or gravel). Fragmentation and reworking of beach rock generate intraclasts (intra-formational clasts; Folk 1959) which range in size from boulders (as slabs), to pebble-sized to sand sized calcarenite fragments and slabs of coquina.

The coastal stratigraphic packages in varied oceanographic/drainage basin settings

From the descriptions above, it is apparent that there is variability in the coastal sedimentary patterns in relation to processes, sedimentary particles, and sediment types throughout the Kimberley region. The distribution and characteristics of the coastal sedimentary systems in the Kimberley region are complex and vary in response to coastal geomorphic setting, method of emplacement, and geometry of sedimentary bodies. They also vary in terms of their granulometry and composition, and their lithotope and stratigraphic interrelations. Because of the diverse origins, multiplicity of processes, and diverse granulometric characteristics of the coastal sediments, it is not possible to devise a strict hierarchical system for their grouping or classification. For instance, storm deposits (or tempestites) may be coral gravel, rock clast gravel, or shell gravel (and they can be monomictic, oligomictic or polymictic; cf. Semeniuk 2008), or beach-rock slab boulder deposits. This renders difficult a systematic classification of sediments based, in the first

instance, on grainsize, or grain composition, or sediment geometry, or sedimentary origin.

The coastal sediments of the Kimberley region form stratigraphic packages that are grouped into a simplified system of eleven suites, reflecting their coastal setting and hence geometry, and some specific granulometric properties related to origin, sediment types therein, processes of formation, stratigraphy, and complexity of stratigraphy. The stratigraphic packages are:

1. Tempestites
2. Block, boulder and gravel shore deposits
3. High-tidal alluvial fans
4. Tombolos and cusate foreland deposits
5. Beach cove deposits
6. Barrier sand/gravel deposits
7. Beach-ridge deposits
8. Sand-and-mud tidal flat systems
9. Mud tidal flat systems
10. Ria and embayment systems
11. Bar-and-lagoon systems

The classification is largely genetic, based on formative processes and on coastal setting, recognising that some lithologies (such as sand, or gravel) transcend the classification categories, and some stratigraphic units or some stratigraphic sequences will occur in more than one classification category. Of the list, for instance, categories 1–9 represent simple stratigraphic packages and form a quasi-gradational series from high energy to low energy. Each category is more or less internally homogeneous and, as such, they are listed in general granulometric order. Categories 10 and 11 represent coastal sedimentary packages that are ensembles of sediments that occur in definite coastal facies arrays within a coastal setting such as an embayment. The wave and tide energy spectrum is more complexly distributed in the ria and embayment systems and bar-and-lagoon systems. In this classification of stratigraphic packages, the emphasis is on coastal sediments and not on *biogenic rock* that also is generated along the coast in the tidal zone but which is outside the scope of this paper (Brocx & Semeniuk, in preparation).

Figure 4 illustrates the plan view of some of these stratigraphic packages. Figure 5 illustrates the occurrence of some of these stratigraphic packages: sandy coves, barriers, and beach ridge plains are generally on the wave exposed outer margins of the ria coast, and the sand-and-mud systems and mud systems are in the interior of embayments.

In terms of stratigraphic complexity, tempestites and block, boulder and gravel shore deposits are relatively simple systems, consisting usually of a single lithology. Tombolos and cusate foreland deposits, beach cove deposits, barrier sand/gravel deposits, and beach-ridge deposits, though dominated by sand, show shoaling systems of various sandy lithology. Similarly, mud tidal flat systems though dominated by mud, show shoaling systems of various mud lithology. High-tidal alluvial fans and sand-and-mud tidal flat systems are more complicated in that they show vertical and lateral lithological changes from gravel to sand to mud. The most complicated stratigraphy occurs within the ria and

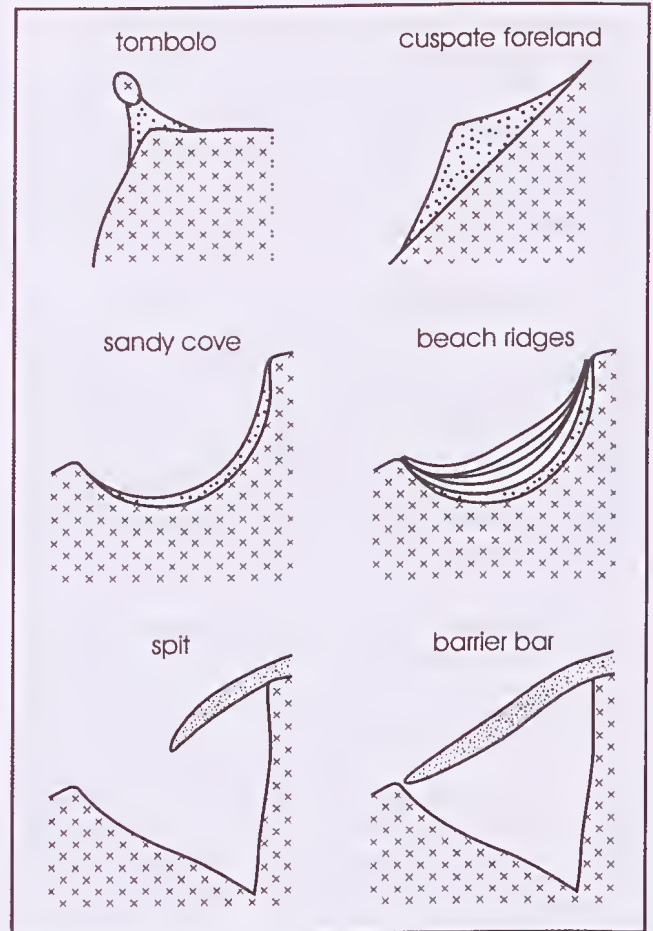


Figure 4. Diagrammatic plan of some selected sedimentary packages.

embayment systems and bar-and-lagoon systems. It should also be noted that the simple stratigraphic (geomorphic) units such as spits, or cheniers, high-tidal alluvial fans, boulder and gravel shore deposits, or tempestites can occur and do occur as stratigraphic units within ria and embayment systems and bar-and-lagoon systems. As such, while most of the sedimentary systems listed above form relatively internally homogeneous packages, even if manifesting shoaling sequences, the ria and embayment systems and bar-and-lagoon systems are sedimentologically the most complex as they have a suite of sediment types (or lithofacies), each with their own specific internal stratigraphic sequence.

While the various sedimentary packages have been separated as categories in this paper, in fact, the tombolos and cusate forelands, beach coves, barrier sand, and beach-ridge systems form a gradational series of coastal deposits geomorphically and a gradational series of stratigraphic packages. Tombolos and cusate forelands, while attached to the mainland or to islands, are deposits that project into the marine environment, whereas beach cove deposits are shore-conforming (shore-hugging deposits), essentially narrow, parallel to, and attached to a broadly indented mainland or open bay, and barrier sand/gravel systems are spits or barriers of sand or gravel located at the mouth of a more deeply indented embayment and form a single barrier across or nearly across the mouth of the embayment. The beach-ridge

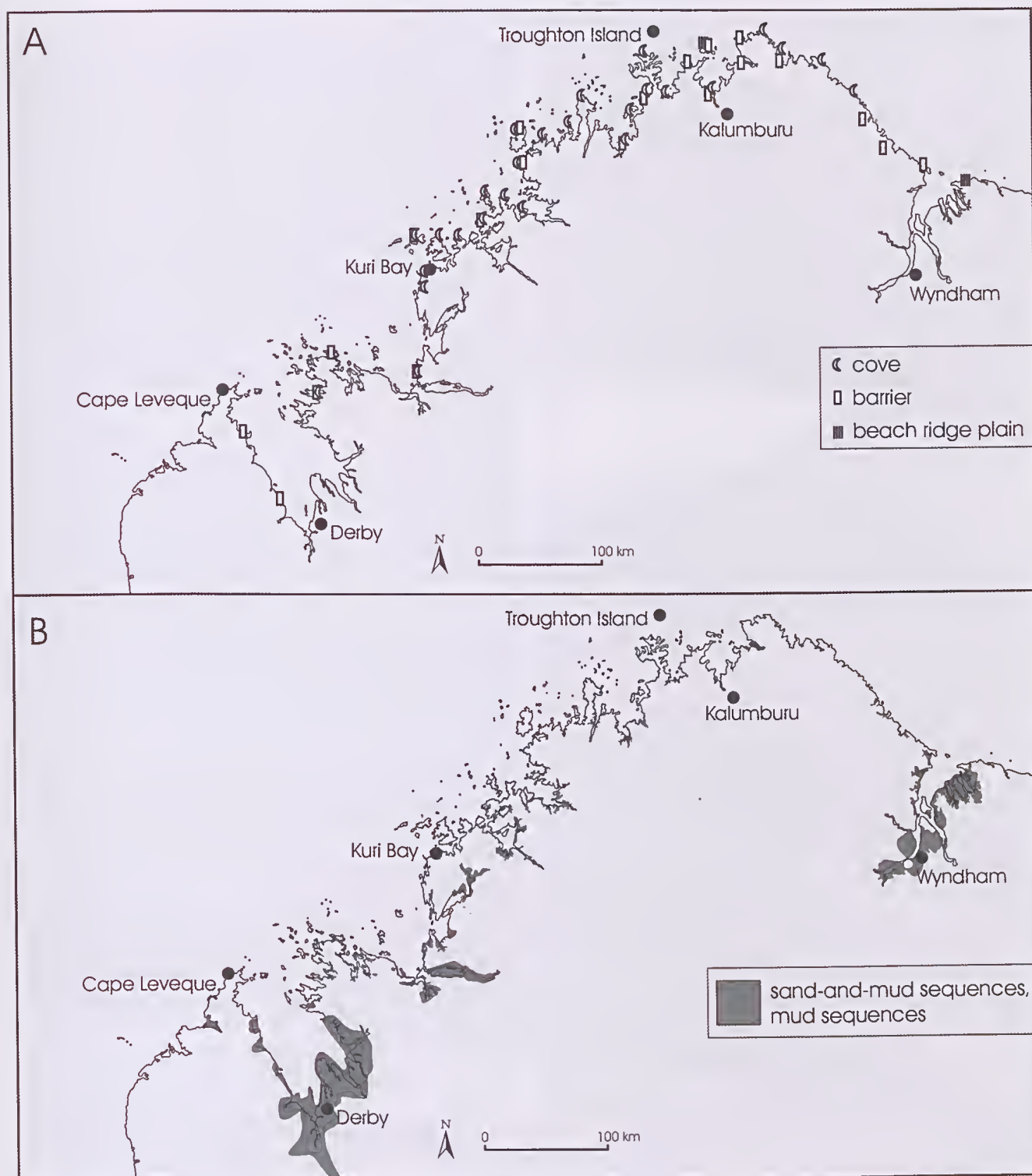


Figure 5. Maps showing occurrences of sandy coves, sand barriers, and beach ridge plains in the wave exposed outer margins of the ria coastal system, and both the sand-and-mud systems and mud systems are in the interior of embayments and gulfs.

systems are similar in setting to the beach cove systems and barrier sand systems, except that the deposits have prograded to form a narrow beach-ridge plain as a prism of sand (usually as a barrier to an embayment).

The sand-and-mud tidal flat systems and mud tidal flat systems generally comprise the tide-dominated deltas

of large funnel shaped gulfs such as King Sound, Stokes Bay, and the Lawley River delta in Admiralty Gulf.

A selection of stratigraphic packages is illustrated in Figure 6, and aerial photographs and on-ground photographs of some of the sedimentary systems are shown in Figures 7 and 8.

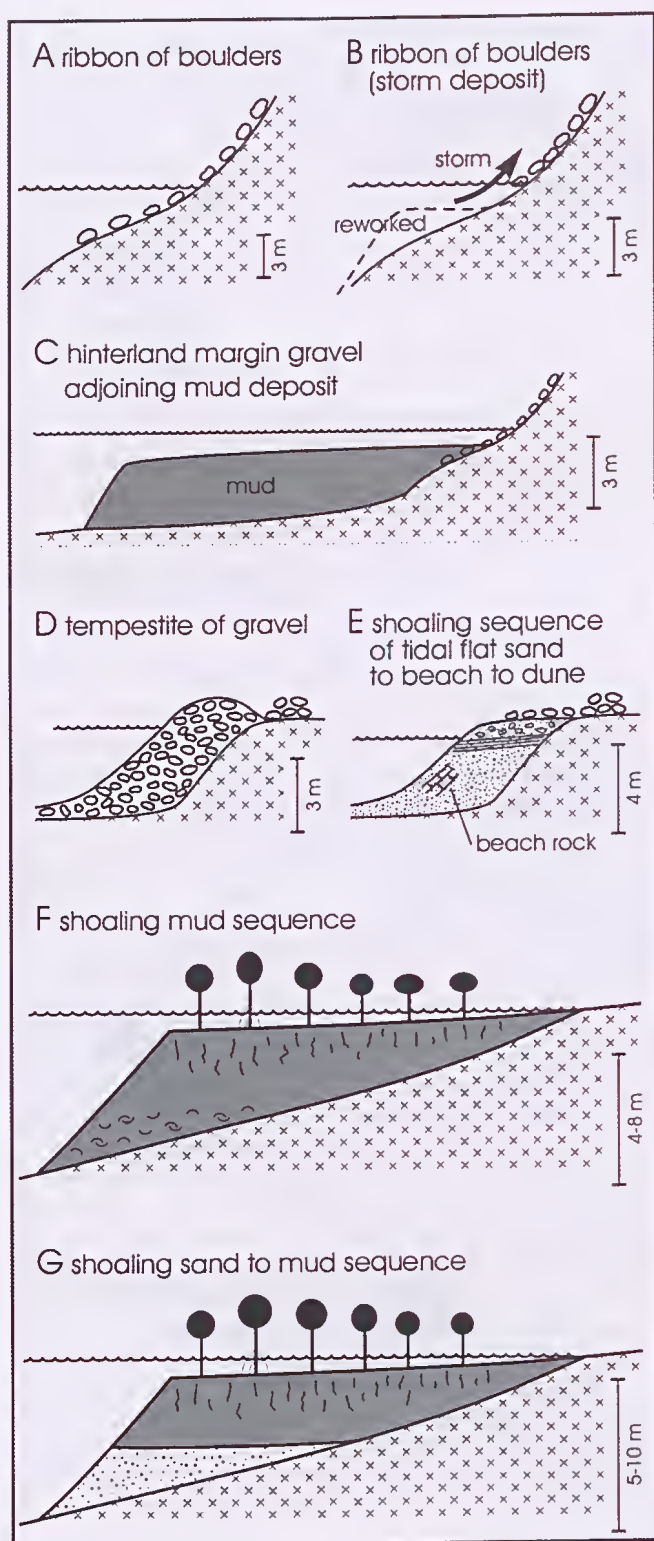


Figure 6. A selection of stratigraphic packages from accretionary systems in the Kimberley region showing their lithologic sequence.

Tempestites

Tempestites are formed by storm processes such as cyclones, during times of high wave energy and generally elevated sea level, resulting from storm surges and low pressure systems. Their emplacement is by shore-directed wave action, or by longshore drift. With the latter, the tempestites commonly emanate from a rocky headland. Tempestites are located in a number of coastal settings and, as such, they comprise a variety of sediment types, but generally, all are located 1–1.5 m above the level of high tide and, locally, 2–3 m above the level of high tide. Compositionally, four types are recognised: Precambrian rock clast tempestites, beach-rock slab tempestites, shell-gravel tempestites, and coral-gravel tempestites.

Along bouldery shores bordering Precambrian rock, Precambrian rock clast tempestites form high level boulder deposits of rock slabs, rock boulders, and equant rock blocks, ~30 cm to 75 cm in size, with some cobble and pebble-sized gravel, but local deposits can be composed of blocks up to 2 m in size. Adjacent to sandstone cliffs or basalt cliffs, the deposits are composed of sandstone blocks and basalt blocks, respectively. Adjacent to sandstone and shale cliffs, the deposits are composed of sandstone blocks and platy shale pebble-sized clasts. Tempestites are ribbon-shaped, several metres wide, and up to 2 m thick, and perched on a rock pavement or rocky slope. Some tempestite deposits, adjacent to sandstone cliffs where joint-controlled blocks of sandstone occur along the rocky shore, are composed of blocks over 2 m in size. These latter tempestites form ribbon deposits several metres thick, and tens of metres wide. Tempestites also form gravel spits emanating from headlands and, as such, can bar embayments. Stratigraphically and lithologically, tempestites generally are structureless deposits, with randomised blocks and cobbles, but locally, there is interlayering exemplified by boulder shapes, and sizes, or layers of pebbles, or (minor) interstitial shell gravel. They have been emplaced by storm-reworking of bouldery shores, or storm-wave alongshore transport. Gravelly tempestites (as “gravel ridges”) were also noted in the Kimberley region by Nott (2006).

Where there is beach rock in mid to high tidal areas, the cemented beach sand can be fragmented and transported shorewards during storms to form tempestites composed of beach rock slabs (*cf.* Semeniuk 2008 for the Canning Coast). Stratigraphically and geometrically, these tempestites are ribbon-shaped, several metres wide and up to 1 m thick, and slope towards the beach. Generally they are structureless deposits, composed of randomly oriented to weakly imbricated slabs of calcarenite or shelly calcarenite or shell gravel (reflecting the variable composition and layering of the parent beach rock), usually 30–45 cm in size and 10–20 cm thick. At above-tide levels in any

Figure 7. Aerial photographs of some of the sedimentary systems along the Kimberley Coast. A. Ribbon of boulders and pebbles along a bouldery shore. B. Ribbon of boulders along a bouldery shore and, to the left, a pocket beach (sandy cove). C. Ribbon tempestite composed of slabs of beach rock (located above the high tide level). D. Bars of coarse sand (as tempestites) as barriers to lagoons and, in foreground, a shore-fringing ribbon of gravel (tempestite). E. Tempestite comprising boulders of sandstone located above the high tide level. Structural benches cut into the sandstone in the inter-tidal zone are evident to seaward of the tempestite. F. Rounded cobbles and pebbles mainly of basalt (and some sandstone) adjoining a cliff where sandstone overlies basalt. G. Tempestite located above high tide level, composed of platy pebbles of sandstone and shale and oyster gravel; the tempestite shows lithological differentiation across the accretionary zones. H. High-tidal alluvial fan debouching onto the high-tidal flat.





locations, where they have been emplaced into the lithosome of dune sands and beach ridges, interstitially, aeolian sand forms a matrix to the boulder frame.

Where molluscan shell has been winnowed, concentrated and transported shoreward by waves, and where oysters, other rocky shore molluscs, and barnacles have been eroded and reworked from rocky headlands, local shell gravel deposits can accumulate. During storms and cyclones, these shell deposits are concentrated, transported, and emplaced in high tidal levels to form shell gravel tempestites above the level of high tide. Though dominantly composed of shell, there also may be a mixture of some pebble-sized sandstone and shale rock fragments where there is local bedrock outcrop. As such, this shell gravel can be monomictic (composed dominantly of one mollusc species), oligomictic (composed dominantly of a few mollusc species and coral), or polymictic (composed of many mollusc species, and with coral and rock fragments). Stratigraphically and geometrically, these tempestites are ribbon-shaped, several metres wide and up to 1 m thick, and usually perched on a beach sand deposit further up the beach slope. Internally, they are layered deposits, with oriented shell and platy gravel.

Beach areas landward of coral communities have coral gravel tempestites. During storms and cyclones, coral gravel is concentrated, transported, and emplaced in high tidal levels to form these tempestites above the level of high tide. Though dominantly composed of gravel-sized coral fragments, there is also local shell, and some pebble-sized sandstone and shale rock fragments, and as such, the gravel can be monomictic, oligomictic, or polymictic. Stratigraphically and geometrically, these tempestites are ribbon-shaped, several metres wide and up to 1 m thick, and usually perched on a beach sand deposit further up the beach slope. Internally, they are structureless to weakly layered deposits, with oriented shell and aligned coral gravel.

Block, boulder and gravel shore deposits

Block, boulder and gravel shore deposits form along rocky shores bordering Precambrian terrane. They are shore-blanketing deposits of rock slabs and equant lithoclasts, generally ~30 cm to 75 cm in size between high water and subtidal levels. Usually, because of wave action at the shore, the rock clasts are rounded. Composition of clasts reflects local provenance. Sandstone cliffs and basalt cliffs produce sandstone clasts and basalt clasts, respectively; adjacent to sandstone and shale cliffs, the deposits are sandstone blocks and platy shale pebble-sized clasts. The deposits are ribbon-shaped, usually blanketing the entire tidal interval, and hence are up to tens of metres wide; they are usually thin (a few 10–30 cm thick). Block, boulder and gravel shore deposits are generally structureless, and may have some admixed

shell, and interstitial sand and/or mud. Block, boulder and gravel shore deposits have formed locally by the erosion and reworking of rocky shores and terrestrial scree slopes, that have been inundated by the post-glacial marine transgression. Wave processes result in abrasion and rounding of the clasts, and in transport of sand into the lithosome. Mud accumulates interstitially by tidal current processes.

High-tidal alluvial fans

Where creeks and streams and some small rivers enter high tidal flats or the marine environment, high-tidal alluvial fans develop (Semeniuk 1985). These are usually located at EHWS but can topographically descend to levels of MHWS. In plan, they are fan-shaped to digitate deposits, up to 500 m long, and 100–200 m wide. In down-dip cross-section, they are usually asymmetrically lens-shaped, thin at their landward part, thickest in central parts (1–2 m thick), and thinning seawards. At their seaward margin they interfinger with, or underlie high tidal mud deposits. Stratigraphically and lithologically, they comprise interlayered gravel and sand and some mud (usually at high tidal parts, or at levels of EHWS and above), or interlayered sand, muddy sand and mud. Compositionally, the gravel is rock clasts, the sand is quartz, and the mud is terrigenous clay and silt. They may have some admixed shell derived from the resident high-tidal molluscs. This lithosome is maintained by fluvial processes delivering gravel, sand, and mud as an alluvial fan, with mud also being transported into the site on the highest tides.

Tomboles and cusped foreland deposits

Where there is a shoreline supply of sand and wave action, nearshore islands adjacent to the mainland coast and clusters of islands act to accumulate sand in the relatively protected leeward zone, as tomboles or as cusped forelands. Wave action is the dominant sedimentary process. These deposits accumulate essentially in high wave energy settings and sand forms elongate to triangular bodies in shoaling sequences. Sediment is supplied from alongshore or from offshore, and is composed of quartz sand, fragmented skeletal biota, and some shell gravel. The stratigraphy of the deposits is a shoaling sequence of burrowed to layered sand (equivalent to low tidal zones), laminated sand (mid tidal zones), and layered sand and shell sand and local shell gravel (equivalent to high tidal zones).

Beach cove deposits

Beach cove deposits are shore-conforming (curved) ribbon-shaped sand and/or gravel deposits that are narrow and parallel to (and attached to) a broadly indented mainland or open bay. The deposits accumulate in high wave energy environments and the sand and/or

Figure 8. Aerial photographs of some of the sedimentary systems along the Kimberley Coast. A. Mouth of a river with barrier bars and leeward lagoons. Seaward of the river mouth is a fan-shaped ebb-tidal delta. B. Tombolo joining a bedrock island to the main shore. C. Barrier of sand barring a narrow ravine. D. Barrier of gravel barring a lagoon (formerly an open embayment). E. Mud deposits filling an series of broad open embayments. F. Aerial photography showing a range of sedimentary features: (1) sandy cove; (2) and (3) barrier of sand composed of parallel beach ridges barring a small lagoon; (4) older spits emanating from headland; (5) older spit barring a muddy lagoon; and (6) mud-filled channel-way vegetated by mangroves and incised by a meandering tidal creek. G. Sand bars and intervening mud-filled lagoons at the mouth of a river outlet. H. Accretionary lobe of mud (with zone mangrove vegetation cover) in a mud-dominated sedimentary system. I. Beach cove system; from left to right, bioturbated sand in the low tidal zone, laminated sand in the tidal zone, and cross-laminated and structureless (vegetated) sand in the supratidal dune zone.

gravel form deposits parallel to the shore. If composed of sand, aeolian transport mobilises sediment from high tidal parts of the beach to form dunes. For sand, the stratigraphy of the deposits shows a shoaling sequence and comprises four units: a low tidal burrowed to layered sand, a mid-tidal mainly burrowed sand, high-tidal layered to structureless sand and shelly sand (and local layers of shell gravel), and a supratidal aeolian structureless to root structured sand. For gravel, the stratigraphy of the deposits is generally a structureless gravel aggregate, but clasts may be imbricated or be aligned if the clasts are platy. Supratidal parts of the system may have a stratigraphic capping of tempestite, which often has interstitial aeolian sand.

Barrier sand/gravel deposits

Barrier sand/gravel deposits are spits or barriers of sand or gravel located at the mouth of a deeply indented embayment, forming a single barrier across the embayment. The deposits are prism-form or shoe-string in geometry, but the process of formation, and sedimentary accumulation is similar to that outlined for the beach cove systems. The stratigraphy of the sand deposits shows a shoaling sequence comprising four units: a low tidal burrowed to layered sand, a mid-tidal mainly burrowed sand, high-tidal layered to structureless sand and shelly sand (with local shell gravel), and a supratidal aeolian structureless to root structured sand. As for the beach cove deposits, supratidal parts of this system also may have a stratigraphic capping of tempestite, which commonly has interstitial aeolian sand. Barriers composed of gravel are mainly rock gravel deposits that are internally structureless or imbricated. Barrier sand deposits along the Kimberley Coast were also noted by Short (2006).

Beach-ridge deposits

Beach-ridge systems are similar in setting to (sandy) beach cove systems and barrier sand systems except that they have prograded to form a narrow beach-ridge plain as a prism of sand. The processes of sedimentation, dominated by wave and aeolian transport, are also similar. Progradation is manifest by shore-parallel linear beach ridges separated by narrow swales. Geometrically, overall, the beach-ridge systems are prism-shaped deposits that stratigraphically show a shoaling sequence of four units: a low tidal burrowed to layered sand, a mid-tidal mainly burrowed sand, high-tidal layered to structureless sand and shelly sand (with local shell gravel), and a supratidal aeolian structureless to root structured sand. Supratidal parts of the beach-ridge system may have a local stratigraphic capping of tempestite, with interstitial aeolian sand, with ribbons of tempestites commonly buried by later deposits of aeolian sand.

Sand-and-mud tidal flat systems

Sand-and-mud tidal flat systems are located in gulfs and embayments where there is riverine influx of sand and mud into a gulf, or tidal transport of sand and mud into an embayment. They comprise some of the tide-dominated deltas in the region (Semeniuk 1981a; Brocx & Semeniuk 2011). The sediments include sand and shelly sand, muddy sand, and mud. Sediment types are

strongly related to tidal level. Low tidal areas are dominated by sand and some shelly sand. Processes here are strong tidal transport by traction, to form megarippled sand and plane-bed sand, and reworking by waves on the rising and falling tide when water depths are <1 m, to form wave ripples. Biota contribute shell, and where this is concentrated by winnowing, shelly sand and shell gravel accumulate. The only common burrowing organism is the sand bubbler crab and sand-tube worms. Low-tidal to mid-tidal areas are underlain by muddy sand, or interlayered sand and mud. Tidal currents transport sand, and mud is deposited from suspension during slack water at high tide, resulting in alternating sand and mud layers. Infauna puncture this layered sequence with burrows, but where the sediments are thoroughly burrow-mixed, muddy sand is formed. Mid-tidal to high-tidal areas are dominated by mud deposits that accumulate from suspension on slack water during high tide, and by processes of scour lag and settling lag. The mid tidal to high tidal interval also is the zone of mangroves, which contribute organic material and whose roots structure the sediment. Skeletal organisms, such as molluscs, contribute skeletal material and burrowing organisms, such as crabs, bioturbate the sediment. With progradation and shoaling, the sedimentary facies form a relatively simple sequence of a lower unit of rippled and laminated sand, overlain by interlayered sand and mud, or by muddy sand that, in turn, is overlain by mangrove-structured mud. In King Sound, where the best example of this sequence occurs (Semeniuk & Brocx 2011), the total stratigraphic package is ~11 m thick. Since the various sedimentary units are strongly related to tidal levels, the thickness of the sediment units within the stratigraphic package have thicknesses broadly related to tidal intervals, with sand at the base ~2 m thick, the unit of interlayered sand-and-mud or muddy sand 3–4 m thick, and the mangrove-structured mud ~5 m thick. The delta of the Drysdale River is also relatively large, the largest in the Kimberley Coast sector, and its ocean-facing distal margin manifests numerous spits and cheniers.

Variation on this general sequence occurs where cheniers of sand and shelly sand are developed at levels of MHWS. These bodies are tens of metres long, several metres wide, and 1–3 m thick. They occur perched on or embedded in the mangrove structured mud, often on an eroded base.

Mud tidal flat systems

Mud tidal flat systems are located in embayments, protected inlets, lagoons that have some tidal connection, gulfs where riverine influx is dominantly mud, or there is tidal transport of mud into an embayment. They underlie some of the tide-dominated deltas in the region where mud dominates the sedimentary suite. Locally, mud also accumulates to form "tombolo-like" coastal sediment structures, in mud-dominated areas, extending from a rocky headland or muddy linear shoal to a nearby rocky island. Muddy sediments range from laminated mud, shelly mud, biostromal mud, burrowed mud, and mangrove-structured mud. These sediment types are strongly related to tidal level. Low tidal areas are dominated by burrowed mud and shelly mud. Biota

contribute shell and, where this is concentrated by winnowing, shelly mud and shell gravel accumulate. Burrowing organisms are common. Low tide to mid tidal areas are underlain by laminated mud, biostromal mud (with mussel beds embedded in the mud), and burrowed mud. The mid tidal to high tidal interval is the zone of mangroves, and they contribute plant material and their roots structure the sediment. Skeletal organisms, such as molluscs, contribute skeletal material, and burrowing organisms, such as crabs, bioturbate the sediment. At all tidal levels, dominant processes are strong tidal transport, with accumulation of mud on the slack water at high tide. During rising and falling tides, and during storms, the mud is reworked, and shell can be concentrated into layers. With progradation and/or shoaling, the sedimentary facies form a relatively simple sequence of a lower unit of mud and shelly mud, overlain by laminated, burrowed and biostromal mud which, in turn, is overlain by mangrove-structured mud. In the embayments of the Port Warrender area (Semeniuk 1983, 1985) and in the Lawley River delta and the Charnley River delta (in Collier Bay) where the best examples of this sequence occur, the total stratigraphic package are ~ 8 m thick, but the thickness of the package will depend on the depth of the basin setting where the mud has been accumulating. In the embayments of the Port Warrender area and in the Lawley River delta, since the various sedimentary units are strongly related to tidal levels, the thickness of the sediment units within the stratigraphic package have thicknesses broadly related to tidal intervals, with the lower mud unit ~ 2 m thick, the middle mud unit 2–3 m thick, and the mangrove-structured mud ~ 3 m thick.

Ria and embayment systems

Ria and embayment stratigraphic systems form in coastal settings that are narrow, v-shaped to open ravines and embayments, or bay-like embayments (Semeniuk 1985). The main features for development of sedimentary packages within the rias and embayments are that: 1. the rias and embayments are relatively protected to accumulate mud in their interiors, or barriers of sand as spits partially bar the embayment to create the protected low energy environment for mud to accumulate through scour-lag and settling-lag processes; 2. the accumulations of mud are incised by meandering tidal creeks which, through bank erosion, and sediment redistribution, develop shoaling point bars deposits and shoaling mid-channel shoal deposits; 3. headlands, bordering the mouth of the embayment, subject to wave action, develop rocky shore bouldery deposits; 4. rocky headlands are sites where rocky-shore biota generate skeletal material as oyster shell gravel, rocky shore molluscan debris, and barnacle gravel; 5. skeletal material formed at the rocky shore headland, driven by wave action on the headlands, and by tidal currents, accumulate as spits emanating from the headland and migrate into the embayment; 6. there are buried colluvial slopes of the upland along the margins of the embayment, still fed by sheet wash from the upland scree slopes; and 7. upland creeks, streams, and small river systems continue to deliver fluvial gravel, sand, and mud to the shore to form high-tidal alluvial fans. Stratigraphically and geometrically, the embayment mud deposits are wedge-shaped, and composed of laminated sand or burrowed mud at stratigraphic levels

of low tide, burrowed mud at levels of low to mid tide, and root-structured mangrove-bearing mud at stratigraphic levels of mid to high tide. The point bars along tidal creeks are lunate-lensoid shoaling accumulations, several metres wide and 2–3 m thick, of sand to mud, or mud, or mud-clast conglomerate (where creek bank erosion has yielded an abundance of mud fragments). The mid shoal deposits along tidal creeks, also several metres wide and 2–3 m thick, have similar stratigraphy to the point bars but have elongate lensoid geometry. Headlands bordering the mouth of the embayment have ribbons of boulders and gravel blanketing the shore, several metres wide and <1 m thick. Spits emanating from the headlands are prisms or shoestrings of sand and shell gravel, several metres wide, several metres thick, and tens to a few hundred metres long; their stratigraphy, depending on location along the length of the spit, is crudely layered shell gravel, or skeletal and quartz sand resting on tidal flat mud, or a shoaling sequence of layered sand and shelly sand grading up to crudely layered shell gravel or skeletal and quartz sand. Colluvium along the margins of the embayment is ribbon-shaped, and a few metres wide and <1 m thick; stratigraphically, it is most commonly a structureless or root-structured muddy pebble or muddy cobble deposit. High-tidal alluvial fans are tens of metres to hundreds of metres long and wide (depending on the size of the contributing creek, river, or rivulets), and stratigraphically composed of gravel and sand and mud at the proximal portions, which grade (often interfingering) into sand and mud, and then mud to seawards. The ensemble of alluvial fan sediments and subfacies therein are 1–3 m in thickness.

Bar-and-lagoon systems

Bar-and-lagoon systems form in embayment settings. The embayments can be open and bay-like, or narrow. The main features for development of this sedimentary package are: 1. the embayment is protected enough to accumulate mud in its interior; 2. there is a supply of material as sand, shell, or rock gravel transported by waves, storms, or tide, to bar the mouth of the embayment; and 3. there are rocky headlands to frame the lagoon and act as anchoring sites for the barrier bar. Driven by wave action on the headlands, and by tidal currents, skeletal material formed at rocky headlands accumulates as spits emanating from the headland, or sand is transported by waves and tides into the mouth of the embayment, or gravel is transported alongshore to form a gravel barrier spit. All these deposits function, however, to bar the embayment to form a lagoon. Where sandy, the barrier may accrete to the level where coastal dunes cap the (beach-derived) barrier. In this context, if active, the dunes may be landward-ingressing, and encroach into the leeward lagoon, burying mangroves and/or encroaching into and overlying the lagoonal deposits. At its contact with the rocky headland, the barrier bar often has a narrow tidal creek that exchanges tidal waters between the lagoon and the open marine environment, such that the lagoon is flooded on the high tides. These tidal creeks commonly have an ebb-tidal delta at their mouth. However, some lagoons of a bar-and-lagoon system are wholly isolated from the open marine environment. In many sedimentary respects, the bar-and-lagoon systems have a number of features in

common with ria and embayment systems, *viz.*, rocky headlands with their source of skeletal and rock gravel material, high tidal alluvial fans, and buried colluvial slopes along the margins of the embayment. Except for an exchange channel at one end of the bar, tidal creek networks traversing the mud-filled lagoon are not a common feature of bar-and-lagoon systems, because there is not enough tidal exchange, and therefore tidal currents are not strong enough to generate them. Stratigraphically and geometrically, the mud deposits under the lagoon are wedge-shaped to lenticular units, and composed of mangrove-structured mud at levels of high tide to mid tide, underlain by burrowed mud at levels of mid tide to low tide. The stratigraphy of the barrier depends on its composition. Sandy barriers have a shoaling sequence of burrowed sand, laminated sand, and a capping of dune sands. Gravelly barriers are relatively homogeneous (structureless) or locally imbricated. Shell gravel barriers are layered. The barriers have two types of stratigraphic relationship with the lagoon deposits: 1. they have predated the accumulation of the lagoon deposits, the lagoonal muds onlap and (for sandy and shell gravel barriers) interfinger with the leeward margin of the barrier, or rock gravel barriers are onlapped by the lagoon muds on their leeward side; 2. the barriers postdate the initial accumulation of the lagoon deposits, and here the barrier deposits rest on the lagoonal muds. Where the barrier is in retreat into the embayment, lagoonal muds are exposed along the seaward base of the barrier deposits (Fig. 9). Ebb-tidal deltas are fan-shaped deposits underlain by laminated sand and shelly sand, and bioturbated sand.

The main stratigraphic units in the bar-and-lagoon system are: the barrier deposits, the lagoon deposits, and the deposits associated with the headland and embayment setting (such as colluvium bordering the upland slopes, the tidal creeks, the high-tidal alluvial fans), and the ebb-tidal delta deposits. The stratigraphic geometry and lithologic sequence in the barrier of the bar-and-lagoon system are similar to that described for the barrier sand/gravel system. The stratigraphic geometry and lithologic sequence in the lagoon generally are similar to that described for the tidal mud systems, but some lagoons are filled with sand and/or with mud,

or interlayered sand and mud. The sand within the sand-filled lagoons derives from the fluvial sources that feed the alluvial fans at their head, or from aeolian input from the dune portion of the barrier that bars the lagoon. The stratigraphic geometry and lithologic sequence of the colluvium bordering the upland slopes, the tidal creeks, and the high-tidal alluvial fan within the bar-and-lagoon system are similar to those units described above in ria and embayment systems.

Discussion and conclusions

Though marginal to a plateau underlain by an apparently repetitive sequence of sandstone and volcanic rock (the Kimberley Basin) and folded metamorphic, volcanic, and igneous rock (the King Leopold Orogen), and a relatively even expression of regional coastal geomorphology (*i.e.*, the array of rias, albeit in different sizes, shapes and orientation; Brocx & Semeniuk 2011), the coastal sedimentary environments of the Kimberley region, present a diverse system of stratigraphic suites that embody a variety of recognisable sediment types, source origins, and depositional style and settings. This variability is expressed in many ways: as the dominance at a given site of gravel *versus* sand *versus* mud; in the origin of gravel at the coast as locally derived *versus* distally derived; in the extent that biogenesis develops sedimentary particles and influences development of sediment types and sedimentary packages; and in the different oceanographic processes prevailing (such as tide-dominated, wave-dominated or cyclone generated conditions) that will sort, transport, shape and emplace the sedimentary bodies. This multitude of primary materials, provenances, and processes are superimposed on coastal settings that include large exposed embayments, smaller exposed embayments, protected embayments, coastal ravines, archipelago coasts, and straight coasts, that have varying orientation in relation to oceanographic aspect. As a result, the array of coastal sedimentary patterns and stratigraphic packages in the Kimberley region is considerable. In each case, the stratigraphy effectively and unequivocally reflects oceanographic setting, coastal setting and form, sediment types and supply, and biogenesis.

As described above, oceanographic factors and the oceanographic aspect of the coast play a large part in determining sedimentary style and type of stratigraphic package. The prevailing and ubiquitous oceanographic condition in the region is the extreme tidal range which results in the development of coastal geomorphic forms of all scales down to small/fine scale sedimentary features. Examples range from the large scale sedimentary accumulations such as the mega-scale tide-dominated delta of the Fitzroy River with its tidally-oriented shoals, to the ubiquitously developed meandering and ramifying tidal creek systems that are erosional on muddy tidal flats, to large fields of sand shoals and megaripples where sand dominates the low tidal areas, to tidal waters delivering mud to areas that are semi-enclosed or protected such that high-tidal mud deposits are ever-present except in wave-agitated areas. Wind waves and onshore wind effects are the next most important and prevailing coastal processes in the Kimberley coastal region, and here oceanographic aspect of the coast becomes a determinant of the



Figure 9. Dark grey mud with *in situ* mangrove stumps exposed along the front of a retreating barrier (leeward of this barrier is a mangrove-vegetated mud-filled lagoon).

sedimentary style and stratigraphic sequence. On exposed coasts, wind waves result in the development of sandy beaches, spits, tombolos, cusped forelands, beach-ridge plains, wave agitated bouldery shores (with rounding of the boulders and pebbles), and dune fields. As such, the best developed sandy beaches, spits, tombolos, cusped forelands, beach-ridge plains occur on the outer exposed parts of the ria shore complex. Cyclones and other storms also have an effect on the coast and, while at times their effects are extreme (e.g., mobilisation of blocks and boulders to above the high tide level), they are not a prevailing process and tend to generate specific coastal forms and coastal deposits, namely erosional features such as mud cliffs along mangrove shores and sand cliffs along beach shores, and depositional features such as cheniers, spits and sand sheets, and the emplacement of block and boulder deposits or skeletal gravel at or above high tide levels as ribbon deposits. The effects of a given cyclonic event or storm are not widespread, but tend to be more localised.

Sediment supply also plays a major part in determining sedimentary style and type of stratigraphic package. Where there is abundant sediment supply, there are large sedimentary accumulations that are subject to the oceanographic processes at a site. To illustrate, the Fitzroy River, with a large drainage basin, and abundant and diverse sediment supply, has large distal accumulations of prograded (tidal flat) sedimentary packages. At the other extreme, rocky shores that shed slabs, blocks and boulders of rock to the coast have a narrow ribbon of bouldery shore deposits, and alluvial fans, that are the distal accumulation of smaller rivers at the head of an embayment, have localised relatively small accumulations of gravel, sand and mud restricted to the high-tidal zone.

The geometry and style of sedimentary accumulations are strongly dependent on the coastal receiving basins (i.e., "basin" geometry or the "basin" wherein the coastal sediments accumulate) developed in the Kimberley region which, in turn, are underpinned by geology of specific lithology and tectonic structure. The rocky coasts of the Kimberley region are controlled by geology, both in terms of rock types, rock structures, and the derivative geomorphology. The fractured rock system of the edge of the Kimberley Plateau, the folded rock system of ridge-and-basin of the King Leopold Orogen, and the landscapes derived from sandstone or basalt bedrock, directly result in a variety of coastal forms from narrow ravines, to narrow embayments, to cliffed shores, rounded shores, rounded embayments, to coastal inundated trellis drainage, fracture and fault oriented gulfs, ravines, and fractured rocks. The shape, size and orientation of the coast as a result of these foundational differences also play a large part in determining sedimentary style and type of stratigraphic package because coastal configuration and "basin" geometry in relation or orientation to coastal processes determine how much sediment accumulates at the coast, what type of sediment accumulates, and the geometry of the sedimentary package. For instance, basalt-based landscapes have developed a different coastal geometry to fractured sandstone based landscapes in terms of coastal forms developed, and type of the seacliffs or shore slopes.

Bedrock geology and the size of the drainage basins of the onshore hinterland have also determined the type and extent of sediment delivery. The largest rivers, axiomatically, have delivered the largest volumes of sediments to the coast, but the type of sediment granulometrically and mineralogically delivered to the coast will be determined by the nature of the source rocks in the drainage basin. Similarly, networks of drainage basins such as those emptying into Cambridge Gulf have delivered large volumes of sediments to the coast. However, leaving aside the largest rivers in the region (*viz.*, the Fitzroy, Meda, May, Prince Regent, Collier, and Lawley Rivers, and the network of the Pentecost, Durack, and King rivers), many of the other smaller rivers in fact are short rivers with relatively small drainage basins, and while they have an influence on coastal development, in that they have incised fracture-controlled gorges and ravines that have been inundated at the coast (forming narrow to open embayments or coastal ravines), they do not necessarily have associated large sedimentary volumes. Bedrock geology has an influence on sedimentary patterns in that sand is derived from landscapes underlain by sandstone, and mud is predominantly derived from landscapes that have a multiplicity of rock types at the drainage basin source (e.g., the Fitzroy River drainage basin and the Pentecost, Durack, and King Rivers drainage basins), or have a basalt landscape (e.g., the drainage basin of the Lawley River). Notwithstanding the influence of distal sedimentary provenance in determining lithology of coastal sediments, there is also the factor of the reworking of earlier Holocene sediments that can generate and deliver large volumes of mud into the modern sedimentary "basin".

The diversity of sedimentary deposits and their stratigraphic dissimilarity are the foundation for the variation and complexity of the coastal ecosystems that occur in the Kimberley region. The variation in coastal substrate types, tidal level of the substrate types, coastal groundwater aquifers and their hydrochemistry, tidal groundwater aquifers and their hydrochemistry, habitats, and the oceanographic processes that maintain the coastal sedimentary deposits and stratigraphic packages, underpin the ecological processes that maintain coastal biota.

The coastal region of the Kimberley, encompassing the Kimberley Coast as a ria coast, and King Sound (including Stokes Bay), and Cambridge Gulf, presents a globally unique ensemble of sedimentary packages. Ria coasts of the style represented along the Kimberley Coast are uncommon in the world (Brocx & Semeniuk 2011). The examples of coasts of comparable extent most similar to the Kimberley region are the indented coasts of Chile, Scotland, and northern Siberia, but these latter coasts actually are fjords (Brocx & Semeniuk 2011) and have a very different suite of sediments, coastal processes and climatic parameters (e.g., coastal processes are underpinned by boreal and arctic climate processes, not tropical processes). In terms of ria coastal types developed elsewhere, the south-west coast of Ireland provides a quasi-comparable coast setting in geometric form, in that geological grain has controlled the form of the rias, but this setting is wholly different in terms of climate, sedimentary suites, and coastal processes. It is

also of limited extent, *viz.*, *circa* 140 km in length of coast as compared to 700 km of the Kimberley ria coast. In this context, the sediment assemblages along the rias of the Kimberley Coast are globally distinct. The nearest equivalents to the Kimberley coastal region either in terms of gulf form or tide-dominated deltas of King Sound, Cambridge Gulf, the Lawley River Delta, and Charnley River delta in Collier Bay are the Colorado River delta on the western coast of the United States of America (Thompson 1969), the Klang-Langat Delta of Malaysia (Coleman *et al.* 1970), and the Brahmaputra River and Ganges River deltas (Allison 1996). The Colorado River delta is similar to the tide-dominated deltas of King Sound and Cambridge Gulf in that it is in a semi-arid climate and manifests salt flats, and is of comparable size. However, it is dissimilar in that it is mangrove-free (and hence lacks the mangrove-generated lithofacies), it is of a smaller tidal range, and doesn't contain the complex Holocene stratigraphy of the King Sound area. The Klang-Langat Delta and the Brahmaputra River and Ganges River deltas are mangrove dominated deltas with mud-dominated deltaic sequences and without the salt flats. In this context, the sediment assemblages along the tide-dominated deltas of the Kimberley region also are globally distinct.

The sediments of the Kimberley Coast are important natural history features of the region, but need to be viewed as ensembles of sediment packages expressed variably across the region. Located in gulfs, in tide-dominated deltas, rias, and with sedimentary suites ranging from cyclone-generated tempestites, to coastal sedimentary suites and mud-dominated sediment systems, and their associated stratigraphic packages developed by macrotidal and tropical conditions, they should be viewed as a heterogeneous and patchy response to the regional abiotic and biotic processes acting on the regional geological template. In other words, there is interplay between coastal processes, coastal forms, sediment supply, and sediment type. Viewed in this manner, the sedimentary packages of the Kimberley Coast as an integrated system are globally unique, and present a model that shows the inter-relationship of coastal morphology, oceanographic factors, sedimentation style and stratigraphic packages.

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King Sound and the tide-dominated delta of the Fitzroy River: their geoheritage values

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Abstract

There are numerous geological and geomorphic features in King Sound and the tide-dominated delta of the Fitzroy River that are of International to National geoheritage significance. Set in a tropical semiarid climate, the delta of the Fitzroy River has the largest tidal range of any tide-dominated delta in the World. Within King Sound, the Quaternary stratigraphy, comprised of early Holocene gulf-filling mud formed under mangrove cover and followed by middle to late Holocene deltaic sedimentation, and the relationship between Pleistocene linear desert dunes and Holocene tidal flat sediment are globally unique and provide important stratigraphic and climate history models. The principles of erosion, where sheet, cliff and tidal creek erosion combine to develop tidal landscapes and influence (mangrove) ecological responses also provide a unique global classroom for such processes. The high tidal parts of the deltaic system are muddy salt flats with groundwater salinity ranging up to hypersaline. Responding to this, carbonate nodules of various mineralogy are precipitated. Locally, linear sand dunes discharge freshwater into the hypersaline salt flats. With erosion, there is widespread exposure along creek banks and low tidal flats of Holocene and Pleistocene stratigraphy, and development of spits and cheniers in specific portions of the coast.

Keywords: King Sound, tide-dominated delta, Fitzroy River delta, tropical climate, geoheritage.

Introduction

King Sound and the tide-dominated delta of the Fitzroy River (Fig. 1) present a unique location globally. The region has one of the largest tide ranges in the World, resides in a tropical monsoonal semiarid climate, hosts the one of the few large tide-dominated deltas, and globally records one of the most complicated stratigraphic sequences for tidal flats. Moreover, in comparison to broadly similar other delta settings or funnel-shaped sedimentary accumulations elsewhere, King Sound and its tide-dominated delta are largely in a wilderness setting.

While the Fitzroy, May, and Meda rivers contribute to the development of tide-dominated deltas in King Sound and Stokes Bay, this paper is an account of King Sound and focuses on the tide-dominated delta of the Fitzroy River, with a description of the coastal forms in the gulf, the reasons underpinning the development of the various coastal types and patterns of sedimentation, and the geoheritage significance of the gulf and delta.

The principles and theory underpinning geoheritage, the scope and scale of features of geoheritage significance, the levels of significance afforded to geoheritage sites, coastal classification in relation to geoheritage, and methods of inventory-based site-identification and assessment have been discussed in Brocx (2008) and Brocx & Semeniuk (2007, 2010a, 2010b)

and the reader is referred to those works. This paper is based on the studies undertaken by Semeniuk (1980a, 1980b, 1980c, 1982, 1983, 1993), with application of geoheritage principles undertaken by Brocx & Semeniuk (2010b).

A description of King Sound and the delta of the Fitzroy River

The depositional system of King Sound and Stokes Bay wherein occur the deltas of the Fitzroy River, May River and Meda River has been determined by the geological grain of the region (Brocx & Semeniuk 2011). The lithological trends, fold trends, faults, and boundary between the various geological units, such as between Precambrian rock massif and Phanerozoic rocks, and those within the Phanerozoic sequences, have been selectively eroded to form the major valley tracts of these rivers. The southern margins of the Precambrian massif also have been incised by short rivers that form tributaries and deliver sediment to these larger rivers. As such, King Sound and Stokes Bay have been partly filled with sediments at their proximal portions with voluminous sediment delivered from these drainage basins (Semeniuk 2011).

In terms of geological setting, King Sound resides at the boundary of the Kimberley Region and Canning Basin (cf. Brocx & Semeniuk 2011). Precambrian rocks form the boundary of the depositional system to the north. A peninsula of Mesozoic rocks (the Dampier

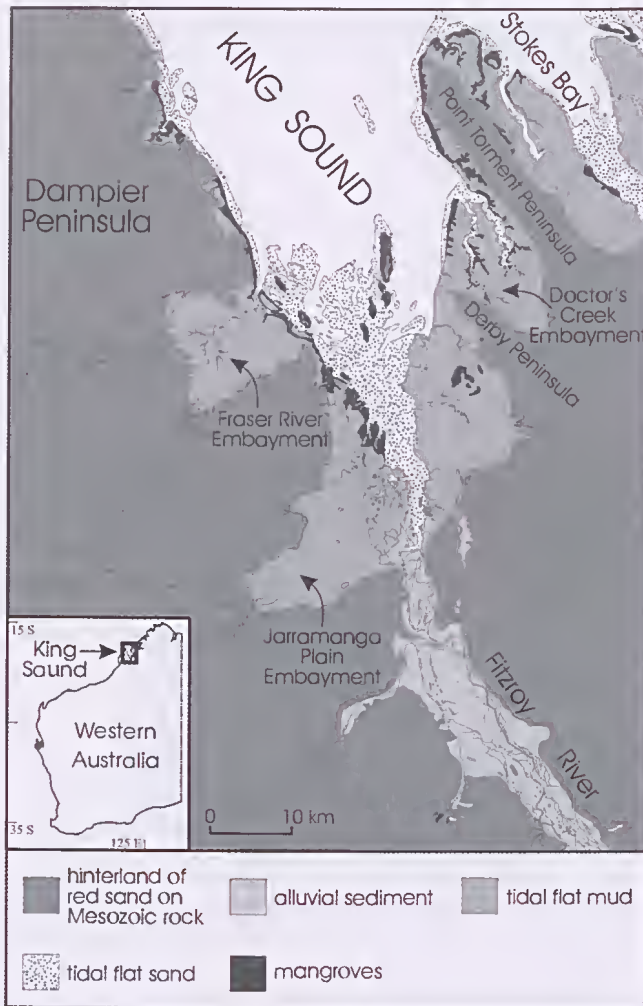


Figure 1. Location map showing King Sound and the tide-dominated delta of the Fitzroy River.

Peninsula underlain mainly by Broome Sandstone) borders the depositional system to the west. A smaller peninsula of Mesozoic rock, the Point Torment Peninsula, internally partitions King Sound in its southern part into two gulfs (King Sound proper, and Stokes Bay). Both terrains of Mesozoic rock are mantled by weathered sandstone, ferruginised sandstone, and Quaternary red sand dunes (Mowanjum Sand).

The greater King Sound is longitudinally partitioned into western and eastern sub-basins by the NW-trending peninsulae of Mesozoic rock (the Point Torment Peninsula and the Derby Peninsula). Though western King Sound is now funnel-shaped, as defined by the contour of MSL, its pre-Holocene shape was more irregular, with a number of embayments to its south. There were/are subsidiary lobate to rectangular to digitate smaller sub-basins such as the Jarramanga Plain embayment, Fraser River embayment, and the Doctors Creek embayment, and were/are sites of relative protection/shelter. In finer detail, the margins of King Sound are crenulate at the scale of 100–200 m because the edge of the funnel-shaped system is demarcated by east-west oriented linear dunes. This crenulate pattern resulted in smaller scale basins of sedimentation located in the inter-dune depressions, which also were sites that were relatively protected/sheltered. In terms of coastal

classification of Brocx & Semeniuk (2010a) it is Coastal Type 7, *i.e.*, landforms constructed by Holocene coastal sedimentary processes that have superimposed erosional features.

Within the depression of King Sound there is a variable Quaternary stratigraphy (Semeniuk 1980c). The sequence consists of Pleistocene Mowanjum Sand (the red sand unit), the Airport Creek Formation (a partially cemented Pleistocene tidal flat unit), the Double Nob Formation (a Pleistocene palaeosol), and the Holocene units of Christine Point Clay (an early Holocene grey mud formed under mangrove cover) and the Doctors Creek Formation (a shoaling sequence of tidal sand to muddy sand and interlayered mud and sand to mud formed in the latter Holocene). Holocene sedimentation and erosion in King Sound followed several basin-filling and erosional episodes (Fig. 2):

1. with rising sea level after the last glacial period, there was an extensive reworking of fine-grained sediment in the region and its shoreward transport, leading to filling of the southern parts of the King Sound embayment and its sub-basins with (mangrove-inhabited) mud, resulting in the accumulation of the Christine Point Clay some 7000 years ago, followed by an erosional episode;
2. in the middle to latter Holocene, deltaic sedimentation resulted in a sedimentary lobe comprised of a sand-to-mud shoaling tidal sediment sequence, capped by (mangrove-inhabited) mud, with delta-land accretion progressing from south to north; the deltaic landscape was dominated by tidally-oriented shoals whose internal stratigraphy is a basal sand to mud sequence; the leading edge of this accreting lobe comprises sand shoals of the interior of King Sound that form the stratigraphically basal sand of the deltaic sequence, and proximal parts of this accreting lobe are the sand-to-mud tidal sequences capped by alluvial sediments that occur to the south of King Sound;
3. concomitant with deltaic accumulation, mud in suspension was delivered beyond the northern margin of the accreting delta (as delineated by the basal sand) to the central and northern parts of King Sound, in advance of the accreting edge of the delta; this mud accumulated in the various relatively protected smaller sub-basins; these accumulations can be considered to be the distal parts of the delta and equivalent to prodelta muds in classic delta sedimentary patterns;
4. throughout this history, the Fitzroy River deposited subaerial floodplain sediments that filled the alluvial valley tract in southern parts of King Sound; these cap the deltaic sediment sequence.

In addition, with erosion cutting into linear dunes along middle to northern margins of King Sound, various spits and cheniers were formed from the eroding tips of the dunes (Jennings & Coventry 1973; Semeniuk 1982). Cheniers also developed on the eroding northern extremity of the central peninsula that faces wind waves, swell, and cyclones.

The delta of the Fitzroy River is a classic tide-dominated delta. The landforms comprise tidally oriented shoals and tidally oriented inter-shoal channel ways. The sequence of sand to mud is also classically deltaic (Morgan 1970) though the difference between the delta of the Fitzroy River and other tide-dominated deltas

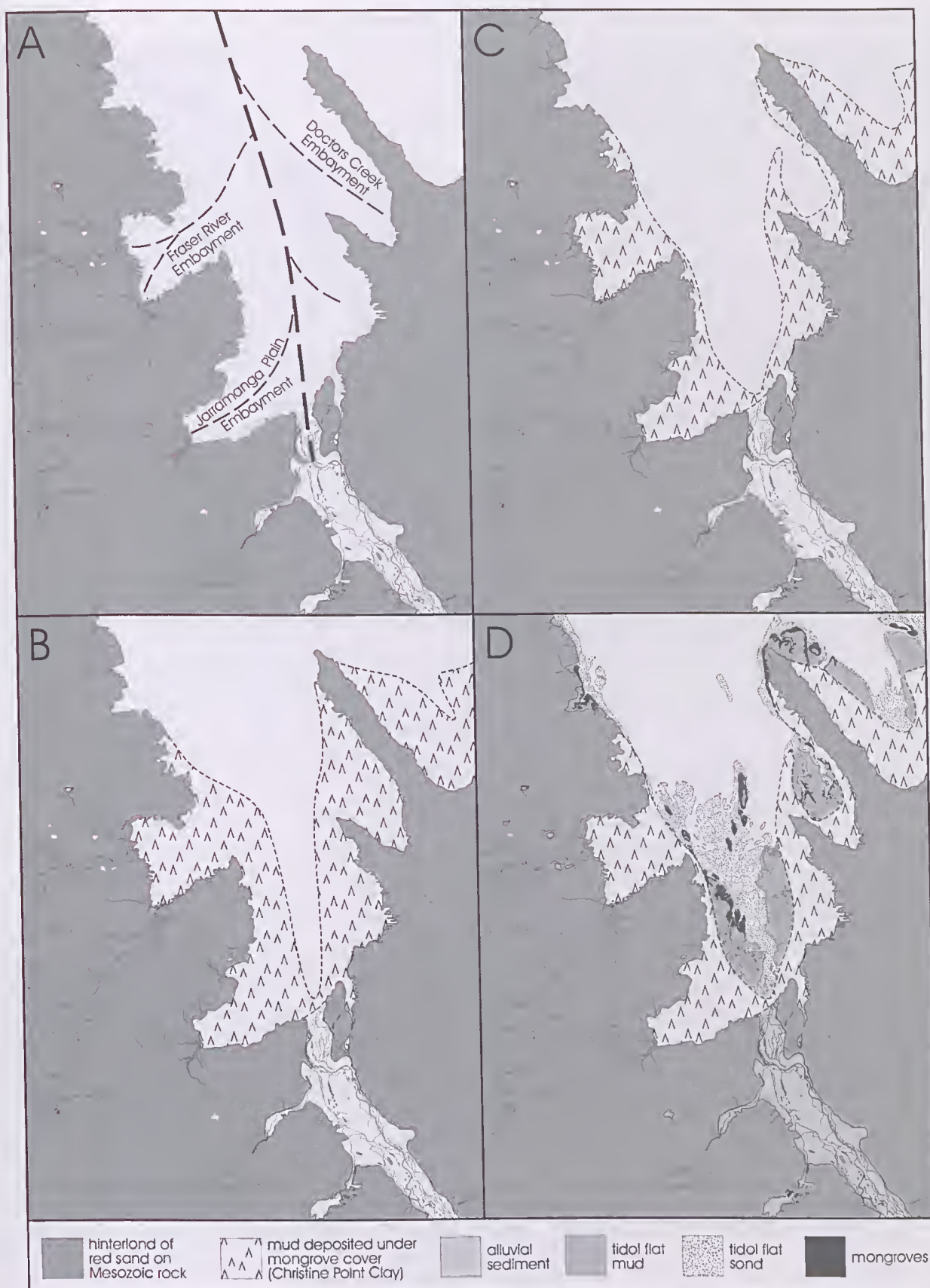


Figure 2. Palaeogeography of the early Holocene King Sound depression and the progressive filling of the gulf with sediments. A. Pre-Holocene and early Holocene palaeogeography showing the course of the Fitzroy River, and subsidiary drainage basins (these subsidiary drainage basins become sub-embayments during the Holocene marine flooding of the area). B. With the Holocene transgression 7000 years ago, southern King Sound was preferentially filled with tidal flat mud (under mangrove cover) forming the Christine Point Clay. C. A major erosional episode followed, resulting in the scouring of the Christine Point Clay. D. On-going deltaic deposition filling the central King Sound depression and the erosional scours cut into the Christine Point Clay, with erosion becoming more dominant in the latest Holocene.

is that it is framed within a bedrock basin and thus was semi-enclosed, whereas other such deltas are open to the sea (e.g., the delta of the Ganges-Brahmaputra Rivers).

The geomorphology of the tidal flats today consists of wide low-tidal flats, underlain by sand or by pavements of partially cemented Pleistocene sediments, followed upslope in turn by narrow mid-tidal flats underlain by Christine Point Clay (with exposure of fossil mangrove stumps) or by modern mangrove-vegetated tidal mud, and extensive high tidal salt flats. Ramifying and meandering across the salt flats are tidal creek networks ranging in width from centimetres to hundreds of metres, and extending in length from tens of centimetres to several kilometres. Tidal creek geomorphology dominates the high tidal flats of King Sound, and is the determinant of tidal landforms (see later). Tidal creek erosion has been a long-term process (Jennings 1975; Semeniuk 1980b, 1982) based on stratigraphic and aerial photographic evidence. Several other features reinforce the conclusions about erosion: nodules under the tidal flats; the imprint of (supratidal) vegetation roots on the substrate; and dieback of modern strandline terrestrial vegetation. The dominantly erosive nature of King Sound results in excellent exposures of Quaternary stratigraphy. Low tidal flats and lower banks of deeply incised tidal creeks expose the Airport Creek Formation, the Double Nob Formation, and the Christine Point Clay and their inter-relationships. Deeply incised tidal creeks exposure the Christine Point Clay and overlying Doctors Creek Formation, and their inter-relationships.

Extensive areas of salt flat in surface layers are riddled with fine rootlet structures that are *unlike* the coarse root structures of mangrove environments. The modern analogue for fine rootlets are grasses on supratidal grassy plains. Such grasses have long since retreated from areas of the now salt flat, but the rootlet structures record the former supratidal conditions, showing that the present salt flats have been developed by sheet erosion of supratidal flats.

Over the Holocene there has been alternating episodes of sedimentation and erosion, with deposition of Christine Point Clay in the early Holocene (some 7000 years ago), followed by its large scale scouring, followed by deposition of a shoaling tidal flat sediments of the Doctors Creek Formation, and then the present phase of large scale net erosion, with cliff, tidal creek, and sheet erosion (Semeniuk 1980b, 1982). This erosion provide a global classroom of such processes on macrotidal tidal flats. In fact, the tidal landscapes of King Sound largely have been determined by tidal erosion, and in particular tidal creek erosion.

Tidal creeks begin their history in crevices of mud cracks and in time deepen, widen and extend their headwaters to landward, progressively evolving to become large and deep meandering systems (Fig. 3). The array of mud cracks coupled with the tidal flat slope generates meandering channels which become entrenched and remain fixed in form through all stages of creek growth. Creeks continue to deepen/widen until the floor is deep enough to intersect the permanently waterlogged muds or sands at a depth where slumping is initiated, and there is a more rapid widening and deepening of the channels; creek cross-sections then change from a shallow v-shape to a deeper u-shape.

Thereafter, erosion is rapid, and creeks widen and deepen in time to form major tidal creek networks the size of Doctors Creek (stage 6 in Figure 3).

Across the tidal flats, groundwater increases in salinity from ~ 40,000 ppm at MSL to ~ 240,000 ppm near the upper edge of salt flats. This salinity gradient transcends various mineral precipitation fields: carbonate is precipitating under tidal flats above MHWS, and gypsum is precipitating under tidal flats further upslope. Nodules of Mg-calcite, aragonite, dolomite, calcite (or their mixtures), often nucleated on crustacean skeletons, such as *Thalassina anomala* and *Uca*, are imbedded in Holocene formations and related to the hypersaline groundwater. Nodules precipitated from hypersaline groundwater within Holocene formations can indicate the extent erosion has proceeded as such nodules, originally formed under salt flats, are being exhumed along seacliffs forming gravel lags.

Fairbridge (1961) identified an important climatic and stratigraphic relationship of Quaternary red sand dunes bordering/underlying the Holocene tidal flat deposits, best developed on the western edge of the Doctors Creek embayment. Later, Jennings (1975) investigated the relationship of these red dunes to the tidal flat deposits, describing the history of the Holocene transgression into the dunes. In the light of the works of Fairbridge (1961) and Jennings (1975), this area has become known internationally and is of International geoheritage significance. It will continue to be a site of stratigraphic and climatic research, as the basic work carried out by those authors is re-explored, refined, and amplified. The red sand dunes descending stratigraphically below tidal flat sediments also provide conduits for freshwater seepage that discharges under the salt flats, e.g., Jennings (1975) documented "dune ghosts" of vegetation surrounded by vegetation-free hypersaline salt flats, and Semeniuk (1980a) documented groundwater salinity diluted by this seepage within buried fingers of dune sand under the salt flats.

The erosional patterns in King Sound influence mangroves ecology and zonation, with different mangrove responses related to cliff, sheet and tidal creek erosion, providing a model of coastal erosion and its relationship to mangrove habitats (Semeniuk 1980a, 1980b). While globally most mangrove areas are viewed as sites where mangrove habitation is linked to coastal accretion, King Sound was the first location where coastal erosion and mangrove ecology were described to provide insight into coastal erosion and mangrove responses. As such it stands as a global classroom for mangrove ecology in relationship to macrotidal coastal erosion (geomorphic geodiversity).

The King Sound area hosts several stratigraphic type sections (Semeniuk 1980c), viz., Mowanjum Sand, Airport Creek Formation, Double Nob Formation, Christine Point Clay, and Doctors Creek Formation (Fig. 4). The Doctors Creek embayment, as the stratigraphic type section for the Christine Point Clay (Semeniuk 1980c) at Christine Point, is the most southern occurrence of the sedimentary unit known as the "Big Swamp" complex of Woodroffe *et al.* (1985) and is an important Holocene climate, stratigraphic, and sedimentologic unit. The "Big Swamp" phase of northern Australia records an early Holocene history of rapid sedimentation, with large mangrove

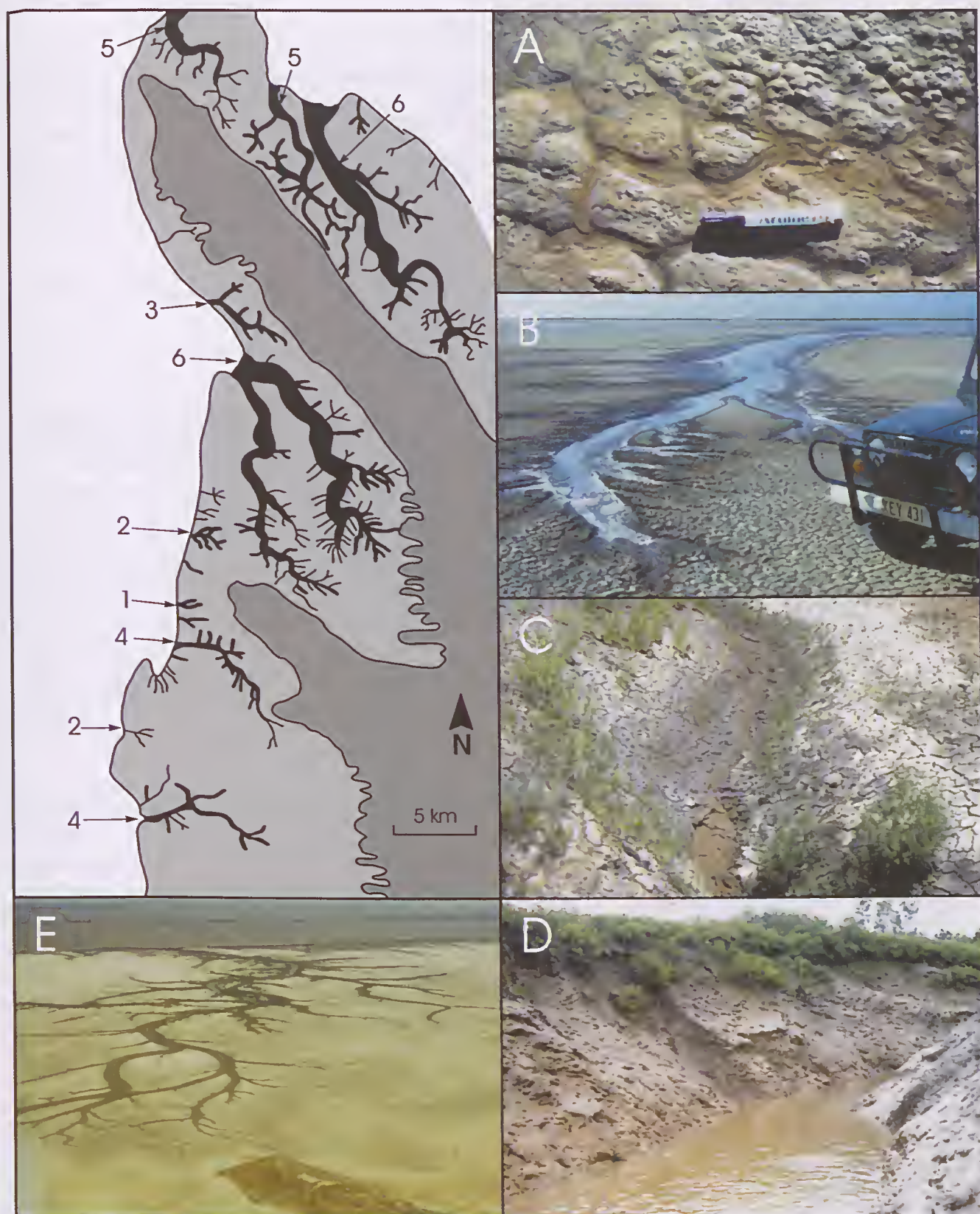


Figure 3. Tidal creek erosion leading to various sizes of creeks in King Sound (after Semeniuk 1980b). Images (A) to (F) show the gradation from creek initiation in mud cracks to large scale meandering creeks; ruler for scale in 'C' is 30 cm. The numbers refer to representative examples of the stages of tidal creek development by widening, deepening and lengthening as described by Semeniuk (1980b) with 1 = the smallest creek and 6 = the largest creek.

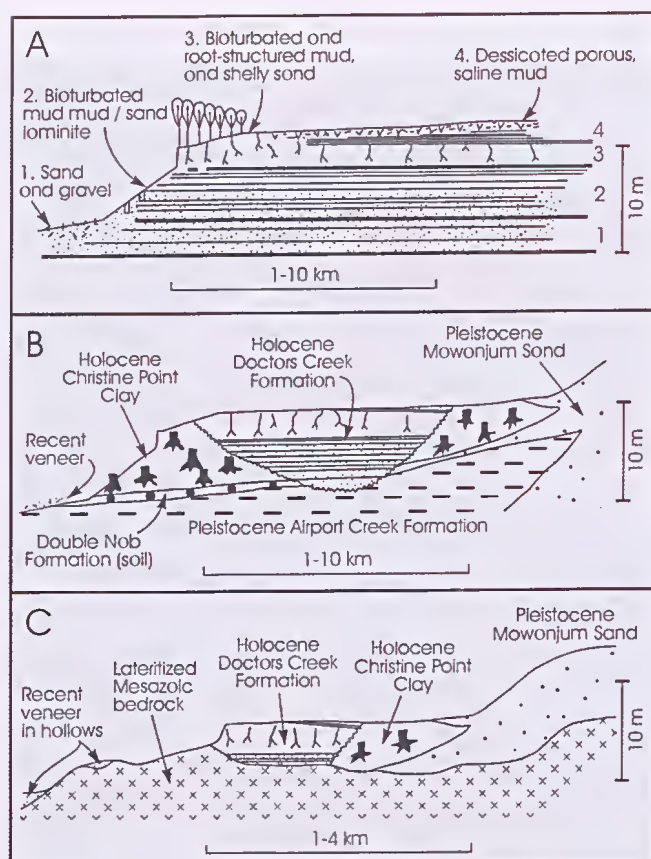


Figure 4. Stratigraphic cross-sections of the tidal flats in southern to central King Sound. A. Doctors Creek Formation of sand-to-mud shoaling stratigraphy. B. Doctors Creek Formation occurring in scours cut into the Christine Point Clay. C. Erosion of Mowanjum Sand to form spits/cheniers, and high-level (truncated) occurrence of Christine Point Clay.

forests, and humid climate, unlike that occurring today in the region. Embedded in this stratigraphic unit at Christine Point, therefore, is the history of this part of Australia in terms of sedimentation style, sedimentation rates, mangrove ecology, and climate.

The geoheritage essentials of King Sound and the delta of the Fitzroy River

From a consideration of the geology and geomorphology of King Sound, the features comprising its "geoheritage essentials" are listed in Table 1. The key features of geology and geomorphology are described in Table 2 with respect to their main characteristics, category of geoheritage site, classification of coast, the scale of the feature, and its level of significance (following Brocx & Semeniuk 2007, 2010a). Many sites of geoheritage significance in King Sound also have cultural significance to the Traditional Owners (*e.g.*, coastal freshwater springs, coastal ecology linked to landscape). It is beyond the scope of this paper to identify such sites and we do not consider that it our place as Western scientists to identify such areas. However, many of the areas assigned below to specific geoheritage categories from an Earth Science perspective could additionally be assigned to one of Cultural Significance by the Traditional Owners of the region.

Table 1

Geoheritage essentials of the King Sound and the Fitzroy River delta
i.e., features of geoheritage significance

tide-dominated delta of the Fitzroy River
principles of erosion (tidal creek erosion and formation of tidal landscapes)
carbonate nodules
Holocene stratigraphy
relationship between Pleistocene linear dunes and Holocene tidal flat sediment
Holocene stratigraphy at Christine Point
Pleistocene stratigraphy
exposure of Holocene mangrove stumps
spits and cheniers
mangroves in response to coastal development
freshwater seepage
stratigraphic type sections

A comparison of the delta of the Fitzroy River with other tide-dominated deltas and macrotidal sedimentary systems

King Sound and its tide-dominated delta are compared with other macrotidal locations globally that have maximum tidal ranges > 10 m (Table 3). King Sound is ranked within the first seven sites globally, but it is clear that it has the largest macrotidal tide-dominated delta in the World. These macrotidal areas are described briefly in terms of their characteristics of climate setting, geomorphic setting, tidal ranges, and occurrence of mangroves. The occurrence of mangroves is noted because they can be an integral part of sedimentation and sedimentary facies, and in King Sound they develop a thick diagnostic lithofacies and the species richness form a rich biostratigraphy not present in sites such as Bhavnagar.

Macrotidal areas that occur in high latitudes lack mangroves and usually have samphires in the upper tidal zone. The estuary of the Sabarmati and the Mahi at Bhavnagar in India is the only other funnel-shaped embayment in a tropical environment that has extreme tidal range. This embayment, however, is an estuary, and it lacks the wide salt flats comparable to King Sound. Further, it is markedly altered by anthropogenic land uses (it is not in a pristine state).

There are numerous other macrotidal estuaries, deltas and tidal flat systems with tidal ranges > 5 m (but generally < 8 m) that do not support mangroves (*e.g.*, the Colorado River Delta; Thompson 1968) – these are not dealt with further here. It should be noted that Bhavnagar, King Sound, and Broome are the only macrotidal systems listed in Table 3 that have mangroves. A comparison of the mangrove-vegetated tide-dominated delta of the Fitzroy River and King Sound with other tide-dominated deltas and other funnel embayment filling sediments systems also shows that the King Sound system is globally unique. Though macrotidal, the Bay of Fundy, The Wash and The Thames (U.K.) are not deltaic, being either tidal embayments or estuarine in terms of sedimentation (Klein 1963; Evans 1965; Yeo & Risk 1981; Prentice 1972). The Klang-Langat delta (Coleman *et al.* 1970) and the combined deltas of

Table 2

Features of geoheritage significance in King Sound and the tide-dominated delta of the Fitzroy River, and the rationale for their assessment

Geological feature	Type of site ¹ , and its scale	Significance	Rationale for assigning the level of significance
tide-dominated delta of the Fitzroy River	modern landscapes and setting (active processes); megascale	International	geomorphic, sedimentologic and stratigraphic description of a tide-dominated delta in a tropical semiarid climate; this is a tide-dominated delta globally with the largest tide
principles of erosion	modern landscapes and setting (active processes); leptoscale to macroscale	International	tidal creek erosion and formation of tidal landscapes provides an international model of coastal development in a tropical, macrotidal environment, particularly in the transition of the small scale to the large scale which provides a powerful natural laboratory
mangroves in response to coastal development	modern landscapes and setting (active processes); mesoscale to macroscale	International	an example of geodiversity where landscape evolution determines mangrove response
carbonate nodules	modern landscapes and setting (active processes); microscale	International	first description of the variety of Holocene carbonate nodules under tropical tidal flats; sets a standard as a type location for Holocene carbonate nodules under tidal flats
Holocene stratigraphy	geohistorical site; mesoscale to macroscale	International	one of the most stratigraphically complex tidal flat systems in the world and also unique because of its tropical and macrotidal setting; well exposed along Airport Creek
Pleistocene linear dunes and Holocene tidal flat sediment	geohistorical site; mesoscale	International	important site for stratigraphic relationship of Quaternary tidal sediments and linear desert dunes, for the model of coastal geomorphic adjustments with sea level rise, and climatic history
Holocene stratigraphy at Christine Point	geohistorical site; mesoscale to macroscale	National	the most southern occurrence of the deposits of the "Big Swamp" phase of the early Holocene of sedimentation in northern Australia and an important indication of climate history and fossil mangrove biogeography
Pleistocene stratigraphy	geohistorical site; mesoscale to macroscale	National	first and only description to date nationally of Pleistocene tidal flat stratigraphy; an important record of Pleistocene climate history, sedimentation, and diagenesis
Holocene mangrove stumps	geohistorical site; microscale to mesoscale	National	outcrop of fossil mangrove stumps embedded <i>in situ</i> in grey clay, extending to below MSL
spits and cheniers	geohistorical site and modern landscapes and setting (active processes); mesoscale to macroscale	National	response of linear dunes to coastal erosion and the effect of coastal process on the exposed northern tip of the Point Torment Peninsula
freshwater seepage	modern landscapes and setting (active processes); mesoscale	National	example of coastal freshwater seepage from dune sand aquifer that has been overlapped by tidal flat sediments
stratigraphic type sections	reference sites; mesoscale	State-wide/ Regional	the area contains a number of stratigraphic type sections

¹ category of site from Brocx & Semeniuk 2007

Table 3

Seven of the largest macrotidal systems globally listed in decreasing order of tidal range

Location	Climate	Geomorphic setting	Max. tidal range (m)	Mangroves
Bay of Fundy (Nova Scotia)	Temperate	rectangular embayment	17.0	none
Mont St Michel (France)	Temperate	funnel-shaped estuary	15.3	none
Severn Estuary (U.K.)	Temperate	funnel-shaped estuary of the Severn	14.6	none
Puerto Gallegos (Argentina)	Temperate	funnel-shaped estuary of Gallegos	13.2	none
Bhavnagar (India)	Tropical semi-arid	funnel-shaped estuary of the Sabarmati and the Mahi	12.2	1 species
King Sound (Australia)	Tropical semi-arid	gulf with tide-dominated delta of Fitzroy River	11.5	11 species
Broome (Australia)	Tropical semi-arid	carbonate-mud tidal embayment	10.5	12 species

(Australian tides from Anonymous 1996; other tidal information from Yeo & Risk 1981; Admiralty Chart 2010; Allen 1970; Knight & Dalrymple 1975; Lasonneur 1975)

the Ganges-Brahmaputra Rivers (Allison 1996) are tropical deltas with dense mangroves (where still intact, though much of the terrain is anthropogenically altered) but with tidal ranges of ~ 4 m. The deltas of the Ganges-Brahmaputra Rivers are particularly interesting as a comparison because they are tide-dominated but open to the sea, and not land-locked like those of the Fitzroy River and Colorado River. The tide-dominated delta of the Yangtze River (Xiqing 1996) is in a subtropical climate and is mesotidal.

The nearest equivalents of King Sound in terms of gulf form and tide-dominated delta of King Sound are the Colorado River delta (Thompson 1968) and Cambridge Gulf, Western Australia (Thom *et al.* 1975). The Colorado River delta is broadly similar to the tide-dominated deltas of both King Sound and Cambridge Gulf in that it is in a semi-arid climate, manifests salt flats, and is of comparable size. However, it is dissimilar in that it is mangrove-free (and hence lacks the mangrove-generated lithofacies), has a smaller tidal range, mud dominates its stratigraphy, and doesn't contain the complex Holocene stratigraphy of the King Sound area. Cambridge Gulf is broadly similar in form to King Sound and also hosts a tide-dominated delta, but its tidal range is 8.4 m, and it has a completely different geological setting (*i.e.*, without linear dunes), being bordered by relatively high-relief landforms of Precambrian and Palaeozoic rocks, and lacks the basal sand that is characteristic of the Fitzroy River delta, *i.e.*, it is a mud-dominated system.

Discussion and conclusions

Microtidal regimes are numerous across the globe (for instance, the well documented systems along the North Sea coast, and the mangrove-vegetated coast of Florida), and they have provided an abundance of sedimentary and ecological/palaeoecologic models for use in Earth-science history in the stratigraphic record. Macrotidal systems are not so abundant, and so any macrotidal system, even if solely a sedimentary system provides important Holocene analogs for the stratigraphic record (Allen 1970; Thompson 1968). In this context, it is important to note that each of the macrotidal systems

located around the globe, such as King Sound, Mont St Michel, the Bay of Fundy, and Broome, provide a different pattern of sedimentation useful to the interpretation of the ancient stratigraphic record (Ginsburg 1975; Semeniuk 2005).

The tide-dominated delta of the Fitzroy River is the only delta globally that is extreme macrotidal and set in a tropical species-rich mangrove biogeographic zone. As such, in terms of geoheritage, it is globally significant. The sediment assemblages of this delta also are globally distinct. Semeniuk (2005) compared stratigraphic sequences from tidal flats around the World with that of the tide-dominated delta of the Fitzroy River – the latter was globally unique in terms of thickness of lithofacies (as related to tidal range), sequence of lithology, and details of lithology. Further, with the occurrence of the early Holocene Christine Point Clay, its scouring and burial with later Holocene deltaic and tidal flat sediments, King Sound manifests the most complex tidal flat stratigraphy recorded to date globally.

As noted in the description of the geoheritage essentials in this paper, there are numerous other geological and geomorphological aspects of the King Sound area that are of geoheritage significance as examples of modern processes operating in tidal environments. King Sound provides a model of tidal landscape development under processes of sheet, cliff and tidal creek erosion, and the development of habitats for mangroves deriving from these processes. Within the stratigraphy and sediments resides information on sedimentation patterns driven by rising post-glacial sea levels, climate changes, and the dynamics of deltaic sedimentation and geomorphic change (Jennings 1975; Semeniuk 1980a, 1980b, 1980c). Within the stratigraphy resides information on Pleistocene aridity during glacial periods and Quaternary coastal sedimentation during inter-glacial periods, and their inter-relationship. The tidal flats also provide a global model for carbonate nodule development, a feature that is often documented in fossil sequences but not in modern environments (*cf.* Semeniuk 2010). The range of carbonate nodules nucleating on Holocene fossils, and the hydrochemistry underpinning these features are a natural laboratory for

unravelling the processes of nodule development, their mineralogy, and environmental setting that would be useful in studies of ancient stratigraphic sequences.

One of the most important aspects of the King Sound area is the natural laboratory that is embedded in the tidal creek systems geomorphically. For those tidal creeks that are meandering and ramifying, the small scale patterns reflect the large scale patterns, and the small scale patterns are embedded in and control the development of the larger scale forms (Semeniuk 1980b). The small scale creek systems, and all intervening creek sizes, could be viewed as miniatures of the larger scale. This aspect of the scalar and geometric nature of the tidal creek erosion contrasts with other tidal systems in the region (e.g., Broome; cf. Semeniuk 2008), because of the climatic, sedimentologic, and vegetational setting of the King Sound. This scalar and geometric property is a powerful and internationally significant feature of the area, which will provide important insights into the processes shaping tidal flat forms.

Many of the other macrotidal systems outside Australia, for instance Mont St Michel, and the Bay of Fundy, and the tide-dominated delta of the Ganges-Brahmaputra Rivers are anthropogenically modified, and in this context, the King Sound system with its tide-dominated delta becomes important in that it is pristine, and constitutes a macrotidal-flat wilderness, unique globally as being a terrigenous and erosional system with the largest tide for a tide-dominated delta and tropical mangrove setting.

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New insights into the Kimberley phytoplankton and their ecology

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Abstract

The Kimberley is a remote region where the eastern edge of the Indian Ocean interacts with the broadening continental shelf of Northern Australia to generate massive tides. During a 2010 research voyage the phytoplankton communities of the region were elucidated from a combination of light microscopy, remote sensing and size fractionated pigment analysis. In strong contrast to previous work from the NW Shelf and the Gulf of Carpentaria $\geq 80\%$ of the phytoplankton at the shelf break (~ 200 m water depth) and further offshore were found to be $< 2 \mu\text{m}$ (picoplankton) and dominated by *Synechococcus*. Streaks of *Trichodesmium* were visible but cell counts suggested they were only the 9th most abundant taxa. Pigment analysis indicated coccolithophorids were consistently $\sim 20\%$ of the total phytoplankton biomass across the region of the cruise. Shelf scale blooms of coccolithophorids are periodically reported in the shallow seas of Northern Australia but only small blooms were observed in MODIS (Moderate Resolution Imaging Spectroradiometer) true colour images from the Kimberley region during the voyage. In shallower waters closer to shore the concentration of phytoplankton rose dramatically. There were concomitant changes in community composition including a decline in *Prochlorococcus* and pelagophytes and a rise in the diversity and abundance of medium to large diatoms. This distinctive, near shore, diatom community was spatially heterogeneous and largely composed of species previously reported as rare in northern Australia.

Keywords: ecology, biogeography, picoplankton, pigments.

Introduction

The Kimberley region is a remote and poorly characterised region of Australia that is currently under significant development pressure associated with resource extraction. In the Kimberley the eastern edge of the Indian Ocean interacts with the broadening continental shelf to generate massive tides. These tides generate considerable mixing creating ecological niches that are not found anywhere else in Australia. Like most of the regional ecology, the phytoplankton are virtually unknown. Joseph Banks noted the presence of *Trichodesmium* in the region during Captain Cook's 1768 to 1771 exploration of the region (Beaglehole 1962). A handful of samples were reported on by Wood (1954, 1964a, 1964b) and a single net sample by Hallegraeff & Jeffrey (1984). In this region variations in ocean colour as observed by satellites have been interpreted as massive coccolithophorid blooms (e.g. Brown & Yoder 1994) yet there has been no *in situ* validation and no research into the impacts of these blooms on carbon cycling and acidification.

The general biogeography of phytoplankton around Australia was broadly investigated by Wood (1954, 1964a, 1964b) with more regional investigations of phytoplankton in the north and northwest of Australia by Hallegraeff & Jeffrey (1984) and Tranter & Leech (1987). Most studies of Australian phytoplankton biogeography (e.g. Wood 1954, Hallegraeff & Jeffrey 1984,

Jeffrey & Hallegraeff 1990) have relied heavily upon net samples which produces a bias against smaller cells. Hallegraeff & Jeffrey (1984) reported that $< 3\%$ of the chlorophyll *a* was $> 15 \mu\text{m}$ in the Australian tropics and the majority of cells were nanoplankton (nominally 2 to 15 μm). Subsequent research has shown that the majority of east coast phytoplankton can be $< 2 \mu\text{m}$ (Crosbie & Furnas 2001, Sorokin & Sorokin 2009). The realization that so many of the dominant taxa in the Australian tropics are small suggests the need for some reappraisal of the phyto-biogeography in this region.

Small phytoplankton are well known to contribute significantly to phytoplankton biomass in oligotrophic open waters particularly the prokaryotic cyanobacteria *Synechococcus* and prochlorophyte *Prochlorococcus* which are often reported to be the numerically dominant species (Olson *et al.* 1990). These small cells which often lack taxonomically useful morphological features for identification when observed by epifluorescence microscopy or conventional light microscopy can, fortunately, be estimated from phytoplankton pigments. In this research pigments that are associated exclusively with one taxonomic group and those with strong associations with a particular taxon are used to investigate the relative abundances of the major taxonomic groups (after Jeffrey *et al.* 1997). For example, pigments such as divinyl chlorophyll *a* (DVchl*a*) are found only in *Prochlorococcus*, zeaxanthin found largely in cyanobacteria such as *Synechococcus*, peridinin (dinoflagellates), alloxanthin (cryptophytes), prasinoxanthin (prasinophytes), 19'-hexanoyloxyfucoxanthin (haptophytes), fucoxanthin

(diatoms), and 19'-butanoyloxyfucoxanthin (pelagophytes).

This paper examines the spatial patterns of the phytoplankton in the Kimberley region as observed on a 3 week research voyage during April to May 2010. A combination of light microscopy, high performance liquid chromatography (HPLC) of phytoplankton pigments and remotely sensed ocean colour were used to investigate the spatial and temporal distributions of phytoplankton in the region. The voyage was planned to occur during the development of the seasonal bloom that peaks in early winter (Fig. 1A). The voyage consisted of a series of onshore – offshore transects from near the coast to > 1000 m water depth. On two occasions samples were collected inside King Sound, once on the spring tide and once on the neap tide. The tides in this region of Australia are amongst the world's largest reaching > 10m. These tides, along with some strong internal waves, provide considerable vertical mixing forces that are proposed to be important in the phytoplankton ecology of the region (Tranter & Leech 1987).

Methods

Data sources and description of data analysis

The research voyage commenced on April 14, 2010 and consisted of 195 vertical profiles of the water column along 5 onshore to offshore transects (Fig. 1B). The 195 profiles were obtained at water depths of: ~ 50, 100, 200, 300, 500, 750, 1000, and 2000 m on each transect. A Seabird SBE 911 instrument (CTD) was used to measure conductivity (converted to practical salinity units), pressure (converted to depth (m)) and temperature (°C). Most vertical profiles also contained photosynthetically active radiation (PAR, 400 to 700 nm, Biospherical Instruments QCP-2300), fluorescence (Chelsea Instruments Aquatracka™ fluorometer), % transmission (Wetlabs C-Star™), dissolved oxygen (Anderra 3975 series optode) and nitrate (Satlantic ISUS sensor) concentrations.

Statistical analysis of the data was undertaken in SigmaPlot version 11. Data sometimes failed tests for homogeneity of variance or for normality even when transformed. When this was the case a nonparametric test was used. The exception was 3 way ANOVA, for which the software did not have a nonparametric equivalent, and it was necessary to rely upon the robustness of ANOVA to deviations from normality and heterogeneity (Sokal & Rohlf 1995).

Remotely sensed observations

The seasonal distribution of phytoplankton were assessed using the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) which operated from September 1997 and collected ocean colour data in the visible and far red region of the spectrum (412, 443, 490, 510, 555, 670, 765, 865 nm wavelengths). The 10 years (September 1997 to September 2007) of SeaWiFS level 3 ocean colour (chlorophyll *a*) data were obtained from the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure (GIOVANNI) as part of the NASA's Goddard Earth Sciences (GES) Data and Information

Services Center (DISC). While at sea daily updates of chlorophyll *a* and true colour MODIS images were received from NASA and used to assist with the selection of sample locations.

Pigment and cell count sampling and processing

On each of the 5 transects there were a series of stations in water depths of ~ 50, 100, 200, 500, 1000 and 2000 m (Fig. 1). Samples for cell counts and HPLC pigments were routinely obtained at 50, 200 and 1000 m deep stations and sometimes at the other stations. Pigment and cell samples were obtained at least every 12 hours throughout a complete tidal cycle and at the surface and deep chlorophyll *a* maximum (DCM) at the 50, 200 and 1000 m stations. Water samples were obtained from General Oceanics Niskin bottles, kept dark and cool until filtered. Samples for pigments were

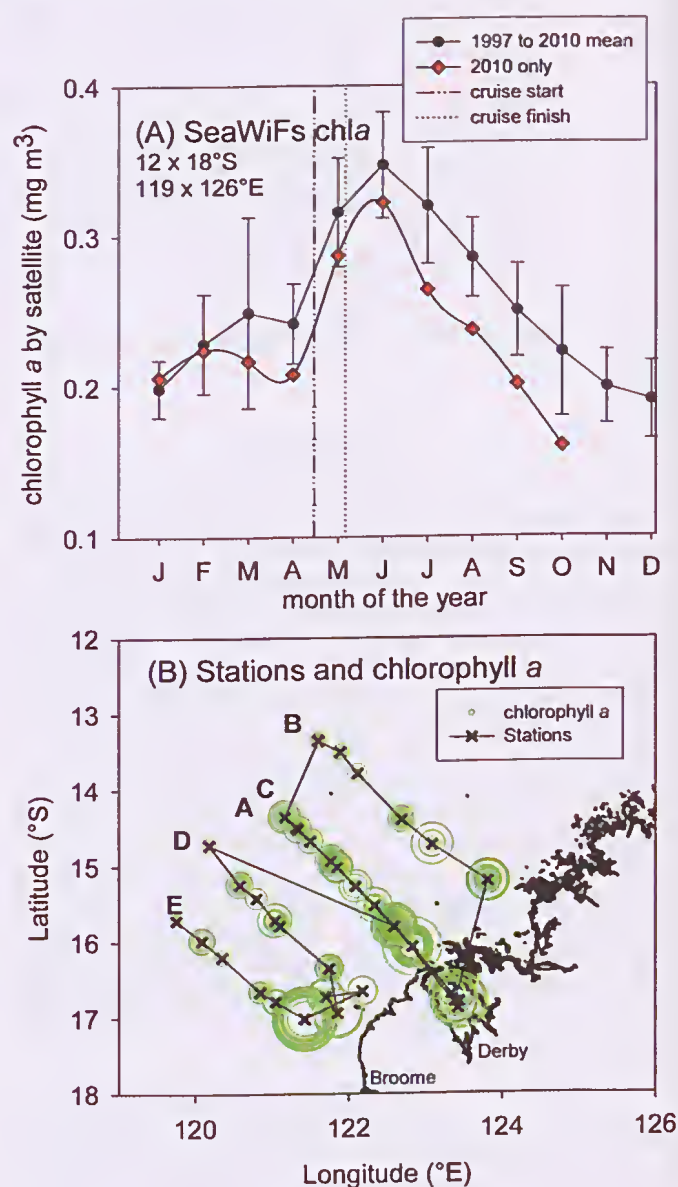


Figure 1. The phytoplankton biomass in the Kimberley region. (A) From SeaWiFS the average ± 1 standard deviation for chlorophyll *a* from 1997 to 2010 plus monthly average for 2010. (B) A map showing the stations and relative chlorophyll *a* concentrations observed during the April to May 2010 research voyage.

obtained by filtering through a range of filter types and pore sizes. Glass fibre filters (Whatman GFF®, nominally retains particles > 0.7 µm) or polycarbonate (Poretics®) filters with 0.2 µm pore sizes were considered to give 'total' chlorophyll *a*. At 105 stations size fractions were collected using a stacked filtration apparatus with a nylon mesh with 5 µm square holes followed by glass fibre filters from both the surface and chl_a_{max}. Other size fractions were obtained from a subset of stations (n = 44) and only the chl_a_{max} using Poretics® filters with 20, 10, 2 and 0.2 µm pores. Sample volumes were variable but typically ranged from 1 to 5 L. Concentrations of all pigments were determined from standards (Sigma™ or DHI Denmark). For pigment analysis by fluorometry, filtered samples were immediately extracted in 90% acetone for 24 h at -20°C (Parsons *et al.* 1984) and analysed on a calibrated Turner model 10AU. Separate samples were stored in liquid nitrogen and analysed by high performance liquid chromatography (HPLC) following the methods of Van Heukelem and Thomas (2001) giving partial resolution to chlorophylls *c*₁ and *c*₂, and full resolution of MV and DV chlorophylls *a* and *b*, lutein and zeaxanthin. CHEMTAX (Mackey *et al.* 1996) was used to convert pigment concentrations into taxa. The expected ratios of various pigments to chlorophyll *a* for various taxa were derived from published literature (Andersen *et al.* 1996, Mackey *et al.* 1996; Lewitus *et al.* 2005; Latasa 2007, Marty *et al.* 2008). CHEMTAX is widely used for this purpose and is amongst the most rigorous methods but, while many phytoplankton taxa have very specific pigment signatures this is not universally true, and there is an unquantified error in the conversion from pigments to taxa. In addition to errors associated with pigments that occur in more than one taxon there are variations associated with temperature, irradiance and nutrient status (Laza-Martinez *et al.* 2007).

Water samples for phytoplankton were examined live using a Leica DM 1000 microscope capable of fluorescence excitation at 450 nm and detection at > 515 nm providing qualitative information on whether some taxa were autotrophic or heterotrophic or contained biliproteins (e.g. allophycocyanin, phycocyanin or phycoerythrin) or chlorophyll *a*. Samples were preserved using acid Lugol's solution (Parsons *et al.* 1984). The preserved samples were transferred to 1-litre measuring cylinders, measured and allowed to settle for at least 24 hours. After this time, approximately 90% of the volume was siphoned off and the remaining sample was transferred to a 100 ml measuring cylinder, measured and again allowed to settle. After at least 24 hours approximately 90% of the volume was siphoned off and the final volume recorded before the remaining sample was thoroughly mixed and an aliquot was taken for counting. The aliquot was put into a 1 mL Sedgwick Rafter counting chamber and examined using an inverted Olympus IX 71 microscope. For most microplankton (cells generally larger than 20 µm diameter) at least 10% of a single slide was enumerated at 100 × magnification (except for species present at very high densities which were estimated from 2%). For nanoplankton, (2 to 20 µm in diameter) the chamber was examined at 400 × magnification until at least 200 cells of the dominant nanoplankton "taxon" had been counted. Small flagellates (< 10 µm in diameter) in the nanoplankton were assigned to a single group (reported as "small

flagellates") unless they could be readily identified as either dinoflagellates, chrysophytes, cryptophytes, prasinophytes or haptophytes. The use of light microscopy and relatively low magnification was insufficient to identify all taxa to species level.

Results

Based on ocean colour data the normal seasonal phytoplankton dynamics for the region of the cruise (12 to 18°S by 119 to 126°E) shows a pronounced minimum in December and a peak in June (Fig. 1A). During April 2010 the phytoplankton in this region were undergoing a strong growth phase with a > 50% increase in biomass between March and May. The cruise dates from April 14 2010 to May 5 2010 were precisely in the middle of this annual bloom (Fig. 1A). The vertical distribution of phytoplankton were assessed from the CTD casts at the 50, 200 and 1000 m stations that averaged: 58 ± 8.8 m (50 m stations), 200 m stations = 188 ± 15 m and 1000 m stations = 1045 ± 21 m (mean ± SE). The DCM ranged from 7 to 85 m; tended to be shallow and weak near shore but stronger and deeper offshore. The concentration of chlorophyll *a* declined ($P < 0.001$) with water depth (and distance from shore) from 0.44 ± 0.035 µg L⁻¹ at 50 m to 0.15 ± 0.037 µg L⁻¹ at 1000 m. In addition to a very strong onshore to offshore gradient in chlorophyll *a* concentrations the spatial patterns suggested increases in the vicinity of the Lacepede Islands and in the waters associated with tidal exchange in and out of King Sound (Fig. 1B).

The principal biomarker pigments (after Jeffrey *et al.* 1997) were divinyl chlorophyll *a* (=DVchl_a found in *Prochlorococcus*), zeaxanthin (found in several taxa but largely in *Synechococcus*), 19'-hexanoyloxyfucoxanthin (=19hex found in haptophytes especially coccolithophorids), fucoxanthin (found in several taxa but largely in diatoms) and 19'-butanoyloxyfucoxanthin (=19but found largely in pelagophytes). The absolute concentrations of these biomarkers except zeaxanthin and 19hex showed very strong ($P < 0.001$) onshore – offshore gradients (Fig. 2A). The concentrations of 19but and DVchl_a rose most strongly, ~ one order magnitude when moving offshore between water depths of 50 and 200 m. Simultaneously the concentrations of fucoxanthin fell six times from 0.14 µg L⁻¹ inshore at 50 m water depth to 0.025 µg L⁻¹ at 200 m water depth at the shelf break, respectively. The pigment 19hex was about two times more ($P < 0.001$) abundant at the shelf break and averaged 3 times ($P < 0.001$) more abundant at the chl_a_{max} than at the surface at the shelf break or offshore stations (data not shown).

The biomarker pigments normalized to chlorophyll *a* show taxonomic trends that can be distinguished from trends due to variation in biomass. Off the Kimberley coast the ratios of all 5 major biomarker pigments normalized to chlorophyll *a* showed considerable change ($P < 0.001$) with water depth (Fig. 2B). The ratios of zeaxanthin, 19hex, 19but and DVchl_a to chlorophyll *a* all rose with increasing water depth while fucoxanthin:chl_a fell. A number of other biomarker pigment:chlorophyll *a* ratios were maximal in the chl_a_{max} found at the shelf break. These included peridinin (=photosynthetic dinoflagellates), prasinoxanthin, neoxanthin,

Table 1

Phytoplankton identified from the Kimberley region during April and May 2010 along transects A and C (see Fig. 1 for details).

Taxa	Biovolume		Abundance	
	Mean (n=12) mL L ⁻¹	Standard error mL L ⁻¹	Mean Cells L ⁻¹	Standard error Cells L ⁻¹
Diatoms				
<i>Amphora</i> sp	1.98 ×10 ⁵	4.18 ×10 ⁶	5	1
<i>Bacteriastrium</i> spp	1.32 ×10 ³	1.40 ×10 ⁴	215	23
<i>Chaetoceros</i> spp < 10µm	6.18 ×10 ⁴	7.76 ×10 ⁵	1639	206
<i>Chaetoceros</i> spp > 10µm	8.48 ×10 ³	1.33 ×10 ³	1461	227
<i>Climacodium</i> sp	6.00 ×10 ⁴	1.73 ×10 ⁴	14	4
<i>Cocconeis</i> spp	6.75 ×10 ⁵	1.95 ×10 ⁵	12	4
<i>Coscinodiscus</i> spp	1.02 ×10 ³	2.34 ×10 ⁴	5	1
<i>Cylindrotheca</i> (=Nitzschia) <i>closterium</i>	7.45 ×10 ⁴	5.32 ×10 ⁵	1380	98
<i>Dactyliosolen</i> spp	6.59 ×10 ³	1.19 ×10 ³	262	48
<i>Diploneis</i> sp	1.41 ×10 ⁵	4.06 ×10 ⁶	4	1
<i>Fragilariopsis</i> spp	6.60 ×10 ⁶	1.90 ×10 ⁶	19	5
<i>Gossleriella</i> <i>tropica</i>	7.08 ×10 ⁴	1.51 ×10 ⁴	5	1
<i>Grammatophora</i> sp	2.97 ×10 ⁵	8.57 ×10 ⁶	7	2
<i>Guinardia</i> spp	1.39 ×10 ²	3.69 ×10 ³	209	47
<i>Hemiaulus</i> spp	9.57 ×10 ⁴	1.29 ×10 ⁴	66	9
<i>Leptocylindrus</i> spp	2.19 ×10 ³	1.29 ×10 ⁴	740	79
<i>Lithodesmium</i> sp	5.03 ×10 ³	1.07 ×10 ³	5	1
<i>Navicula</i> spp	2.91 ×10 ³	5.02 ×10 ⁴	273	19
<i>Planktoniella</i> sol	6.67 ×10 ⁴	1.93 ×10 ⁴	8	2
<i>Pleurosigma</i> spp	2.45 ×10 ⁵	7.08 ×10 ⁶	4	1
<i>Porosira</i> sp	5.54 ×10 ³	1.57 ×10 ³	31	6
<i>Proboscia</i> spp	2.24 ×10 ²	3.45 ×10 ³	20	3
<i>Pseudo-nitzschia</i> spp	7.89 ×10 ⁴	7.94 ×10 ⁵	3875	393
<i>Rhizosolenia</i> spp	9.66 ×10 ³	1.03 ×10 ³	176	20
<i>Skeletonema</i> spp	3.30 ×10 ⁴	6.71 ×10 ⁵	200	41
<i>Synedra</i> sp	9.81 ×10 ⁴	1.68 ×10 ⁴	60	13
<i>Thalassionema</i> spp	6.06 ×10 ⁴	7.65 ×10 ⁵	152	22
<i>Thalassiosira</i> spp	2.48 ×10 ⁴	3.17 ×10 ⁵	56	7
<i>Trigonium</i> spp	1.24 ×10 ³	3.59 ×10 ⁴	2	1
Total diatoms	8.77 ×10 ²	7.69 ×10 ³	10908	804
Dinoflagellates				
Small dinoflagellates 6–8µm	2.77 ×10 ³	1.55 ×10 ⁴	9175	515
<i>Amphidinium</i> spp	7.69 ×10 ⁶	1.03 ×10 ⁶	34	5
<i>Ceratium</i> spp	1.10 ×10 ³	1.74 ×10 ⁴	18	3
<i>Cochlodinium</i> sp	8.34 ×10 ⁵	2.41 ×10 ⁵	7	2
<i>Dinophysis</i> spp	6.52 ×10 ⁵	1.88 ×10 ⁵	4	1
<i>Gymnodinium</i> spp	6.21 ×10 ⁵	5.38 ×10 ⁶	84	7
<i>Gyrodinium</i> spp	1.62 ×10 ²	1.47 ×10 ³	156	14
<i>Ornithocercus</i> sp	2.62 ×10 ⁵	7.58 ×10 ⁶	4	1
<i>Oxytoxum</i> sp	6.26 ×10 ⁴	8.74 ×10 ⁵	29	4
<i>Prorocentrum</i> spp	4.77 ×10 ⁵	8.71 ×10 ⁶	18	3
<i>Protoperidinium</i> spp	1.94 ×10 ⁴	5.61 ×10 ⁵	4	1
<i>Scrippsiella</i> sp	1.80 ×10 ⁴	2.01 ×10 ⁵	38	4
Total dinoflagellates	2.13 ×10 ²	1.56 ×10 ³	9573	515
Flagellates				
Chrysophytes	2.39 ×10 ⁴	4.18 ×10 ⁵	304	53
Cryptophytes	8.63 ×10 ³	6.71 ×10 ⁴	10992	854
Small unidentified flagellates (3 to 10 µm)	7.89 ×10 ²	3.10 ×10 ³	384542	14707
Prasinophytes	7.65 ×10 ⁴	5.91 ×10 ⁵	2921	226
Haptophytes (includes coccolithophorids)	4.76 ×10 ³	1.70 ×10 ⁴	9090	323
Total flagellates	9.32 ×10 ²	3.53 ×10 ³	407849	15389
Cyanobacteria				
<i>Trichodesmium</i>	3.40 ×10 ³	5.85 ×10 ⁴	185	23
Other				
<i>Mesodinium rubrum</i>	4.06 ×10 ³	1.17 ×10 ³	192	55

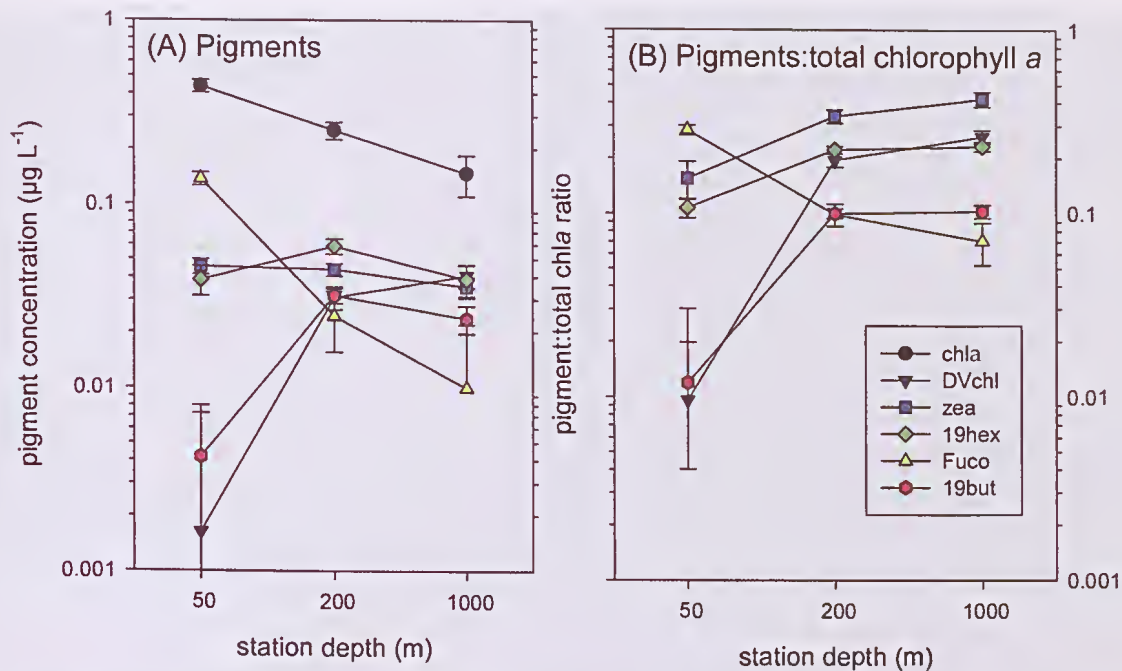


Figure 2. Trends in the concentrations of phytoplankton marker pigments with water depth. Samples were obtained from the surface (0 m) and chlorophyll *a* maximum (7 to 85 m). (A) Strong declines in absolute concentrations of zeaxanthin (*Synechococcus*) and divinyl chlorophyll *a* (*Prochlorococcus*), 19'-butanoyloxyfucoxanthin (pelagophytes), 19'-hexanoyloxyfucoxanthin (haptophytes and coccolithophorids) all increasing offshore, while fucoxanthin (diatoms) fell. (B) Trends in marker pigments normalized to chlorophyll *a* showing community composition changes.

violaxanthin (all indicators of prasinophytes or related algae) and alloxanthin. The latter is synthesized by cryptophytes. All specimens of the dinoflagellate, *Dinophysis miles*, observed live were pigmented with plastids that fluoresced strongly orange under 460 nm excitation (Fig. 3).

The ratios of most pigments to chlorophyll *a* showed significant ($P < 0.001$) trends with sample depth. The exception was the 19hex:chl_a ratio of 0.18 at the surface and 0.20 at the chl_a_{max}. Ratios of fucoxanthin and 19but to chlorophyll *a* both rose with sample depth ($P < 0.001$). DVchl_a and zeaxanthin to chlorophyll *a* fell ($P < 0.001$) with sample depth by 2.2 and 5.2 times, respectively.

The CHEMTAX results showed *Synechococcus* was the dominant taxon in the region peaking at 55% of the biomass offshore (1000m) and in the surface waters (Fig. 4A). In contrast diatoms were ~ 10 times more abundant in the coastal zone (50 m) than further offshore. During the cruise true colour MODIS images provided evidence of patches that appeared to be relatively small coccolithophorid blooms. The species or genera of coccolithophorids were not easily identified in our routine cell counting but will be enumerated using specialized methods (Henderiks and Torner 2006). As discussed above the spatial distribution of the coccolithophorid marker pigment (19hex) was maximal at the chl_a_{max} found at the shelf break. Yet the ratio of 19hex:chl_a and the CHEMTAX output show the relative distribution of haptophytes, was not significantly different with depth ($P = 0.465$). Haptophytes were quite consistently about ~ 20% of the total biomass at the surface and at the chl_a_{max} in all water depths. *Prochlorococcus* was less than 1% of the biomass inshore (50m) and rising sharply to 9 to 22% of the biomass at the

shelf break and further offshore. Similarly pelagophytes were found primarily offshore and strongly biased towards the bottom of the euphotic zone being 3 to 4 times more abundant in the chl_a_{max} than at the surface. A range of taxa including: chlorophytes, prasinophytes and euglenophytes, could have contributed some of the pigments assigned to prasinophytes in this CHEMTAX analysis. This relatively broad taxonomic group was more abundant in 50 and 200 m of water than in 1000 m.

A number of phytoplankton taxa were identified to genus or species using light microscopy. The contribution of these to the total phytoplankton biomass was determined by aggregating to genera and estimating the biovolumes (Table 1). In general the phytoplankton biomass was dominated by large diatoms and dinoflagellates (Table 1, Fig. 3). At the level of genera the large diatom *Proboscia* was the greatest component of the phytoplankton with an average biovolume of 2.2×10^{-2} mL per litre of seawater. The second greatest biomass was from the dinoflagellates where the large species in the genus *Gyrodinium* were the greatest biovolumes. Three species from the widespread genus *Guinardia* were tentatively identified (*striata*, *flaccida*, *delicatula*) and in total these represented the third largest component of the phytoplankton biomass. Large centric diatoms of the genera *Rhizosolenia* were the fourth largest component followed by large ($> 10 \mu\text{m}$) *Chaetoceros* species, *Dactyliosolen*, *Porosira*, *Lithodesmium* species. The ciliate *Mesodinium rubrum* (= *Myrionecta rubra*), a voracious consumer of cryptophytes was 9th followed by the trichome forming cyanobacterium *Trichodesmium*.

The spatial distributions of some genera were reasonably uniform while others were very patchy. Of the taxa with relatively high biovolumes in the region

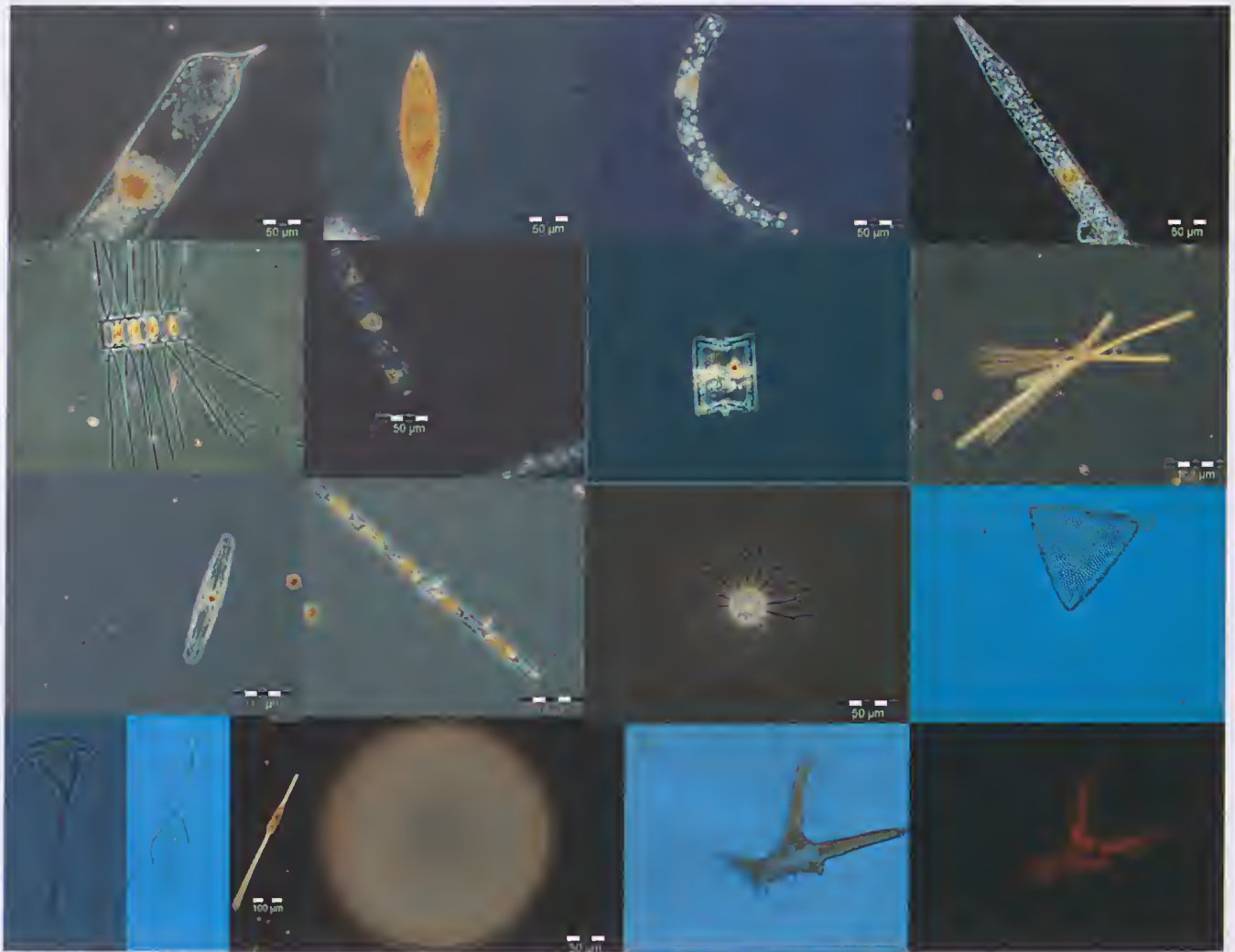


Figure 3. Light micrographs of the dominant taxa found in the Kimberley region. Row 1 (L to R): *Proboscia* sp., *Gyrodinium* sp., *Guinardia* sp., *Rhizosolenia* sp., Row 2 (L to R) large *Chaetoceros* sp., *Dactyliosolen* sp., *Lithodesmium* sp., (~ 100 µm diameter), *Trichodesmium* sp. Row 3 (L to R) *Navicula* sp., *Leptocylindrus* sp., *Bacteriastrium* sp., *Trigonium* sp. Row 4 (L to R) various *Ceratium* spp., *Coscinodiscus* sp., *Dinophysis miles*, *Dinophysis miles* (under epifluorescence).

Mesodinium, *Trigonium* and *Planktoniella* all had coefficients of variation greater than 28%, basically occurring in 1 of 12 samples analysed. In the rare samples where they occurred they tended to dominate the biomass. For example taxa found only once included: *Mesodinium rubrum* which was 14% of total phytoplankton biovolume at the $chl a_{max}$ (75 m) offshore in a 1000 m of water. *Planktoniella* was also found at 75 m in the $chl a_{max}$ but only at the shelf break (~200 m water depth) and *Trigonium* was 9% of total phytoplankton biovolume at the surface and again only at the shelf break. Genera that were high in biovolumes and relatively uniformly distributed included *Gyrodinium*, *Navicula* and *Nitzschia*; all with coefficients of variation $\leq 9\%$. The genus dominant by biovolume, *Proboscia*, was not found in any of the samples from near shore (~50 m) but in 4 of 8 samples from deeper waters.

The size distribution of phytoplankton derived from size fractionated chlorophyll *a* (please note that this includes only photosynthetic species) showed very strong ($P < 0.001$) onshore to offshore gradients (Fig. 5). The picoplankton ($< 2 \mu m$ cells) were dominant everywhere

but they reached their lowest fraction of the total biomass at the 50 m stations; where they were only 54% of total chlorophyll *a*. Phytoplankton cells larger than 20 µm reached 26% of the total chlorophyll *a* at these inshore stations. The portion of phytoplankton greater than 20 µm fell to 3% of total chlorophyll *a* in 1000 m of water. At the same time the proportion of picoplankton rose reaching 84 to 80% of total chlorophyll *a* in 200 and 1000 m of water, respectively.

Discussion

Cell size is one of the fundamental characteristics of a phytoplankton species and of the community because of the strong associations between cell size and the physiological traits such as nutrient and light utilization plus grazer resistance (Banse 1976, Grover 1989, Sterner 1989, Litchman *et al.* 2007). Previously the nanoplankton (>2 and $<15 \mu m$) were proposed to be the dominant phytoplankton group (Hallegraeff and Jeffrey 1984) in the Kimberley but these new results show the majority of the autotrophic phytoplankton biomass were

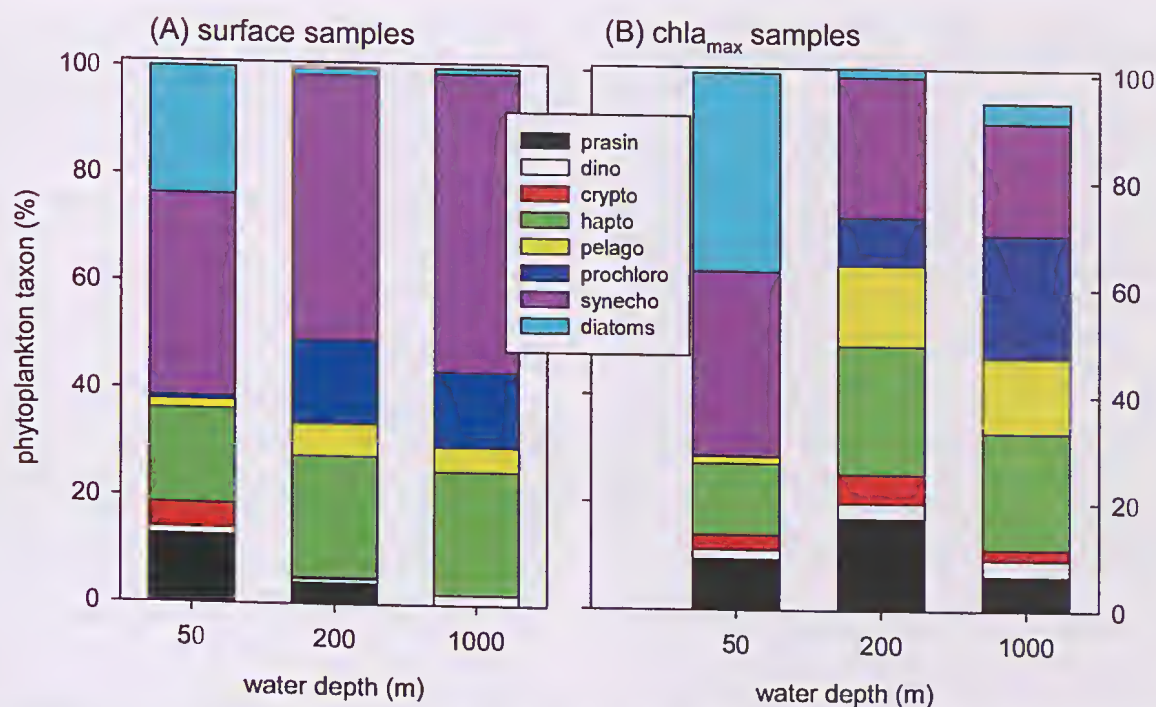


Figure 4. Estimated proportions of major taxa from marker pigments using CHEMTAX (Mackey *et al.* 1996). Abbreviations as follows: prasin = prasinophytes, dino = dinoflagellates, crypto = cryptophytes (also contains *Mesodinium rubrum* and *Dinophysis miles* (see text), hapto = haptophytes (includes coccolithophorids), pelago = pelagophytes, prochloro = *Prochlorococcus*, synecho = *Synechococcus*.

picoplankters ($< 2 \mu\text{m}$), predominantly *Synechococcus* and *Prochlorococcus*. The sampling of size fractionated chlorophyll *a* showed that the portion of autotrophic phytoplankton that were picoplankton peaked at $\sim 80\%$ in the offshore region. These very small cells with a high surface area to volume ratio and low self shading are considered well adapted to stable low nutrient and low light conditions (Raven 1987, 1998). Their very small size also confers considerable resistance to grazing by mesozooplankton and some reduction in grazing by microzooplankton (Monger & Landry 1991). A few

genera, such as *Trichodesmium* *Proboscis*, *Rhizosolenia*, may also escape significant grazing pressure by virtue of their large size.

The sampling regime implemented in 2010 provided strong evidence of onshore to offshore gradients in biomass, community composition, depth distributions and size structure in the Kimberley region. In the offshore samples the vertical differences in phytoplankton biomass and community composition were much greater between the surface and the $\text{chl } a_{\text{max}}$ than those observed near shore. Offshore the deep $\text{chl } a_{\text{max}}$ had $\sim 100\%$ more pelagophytes than the surface. The pelagophytes are a picoeukaryote taxon found broadly across the Indian Ocean (Not *et al.* 2008) and along most of the west Australian coast they increase their dominance with depth (Thompson *et al.* 2010). The presence of a deep chlorophyll *a* maximum and significant community differentiation between the surface and the $\text{chl } a_{\text{max}}$ indicates the stability of the water column in these locations must have exceeded many generations of the phytoplankton (Cullen & Lewis 1988, Cullen 1990) preceding the cruise in April 2010.

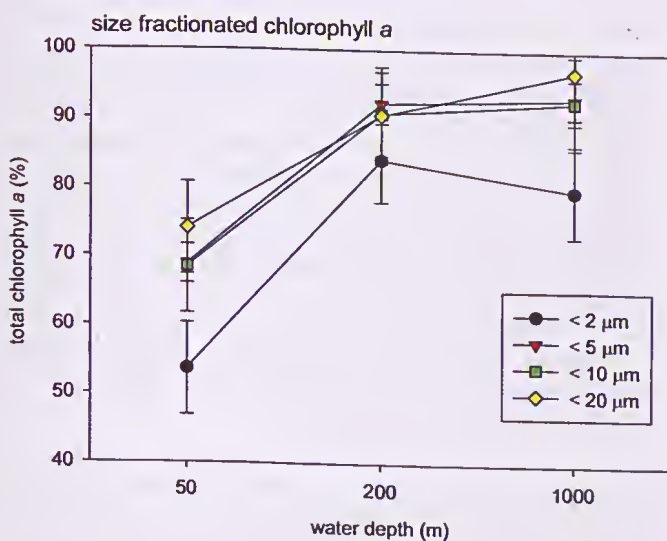


Figure 5. The proportions of chlorophyll *a* found in cells that were less than a particular size (2, 5, 10 and $20 \mu\text{m}$) from near shore (50 m water depth) to offshore (1000 m water depth). For example, 54% of chlorophyll *a* was found in cells less than $2 \mu\text{m}$ where the bottom was 50 m below the surface.

The phytoplankton taxa collected during the April to May 2010 survey (herein) and observed under the light microscope were broadly consistent with those reported from the general region (Conkright *et al.* 2002) and from Northwest Shelf to the Gulf of Carpentaria by Wood (1964) and Hallegraeff & Jeffrey (1984). Of the microplankton, the diatom genera *Proboscis* (formerly *Rhizosolenia alata*), *Rhizosolenia*, *Chaetoceros*, *Bacteriastrum*, *Navicula*, and the dinoflagellates *Gyrodinium*, *Ceratium* and the cyanobacterium *Trichodesmium* were all relatively abundant in the region. The three species of *Guinardia* found in 2010 were reported as common or rare under previous names *Guinardia delicatula* (formerly *Rhizosolenia delicatula*), *Guinardia flaccida* (formerly *Rhizosolenia*

flaccida), *Guinardia striata* (formerly *Rhizosolenia stolterfothii*) by Hallegraeff & Jeffrey (1984). Reported as rare (Hallegraeff & Jeffrey 1984), or not previously reported from the region, were some genera found to be abundant in 2010 including: *Dactyliosolen*, *Porosira*, *Lithodesmium*, *Leptocyldrus*, *Trigonium* and *Coscinodiscus*. Species of *Leptocyldrus*, *Coscinodiscus* and *Trigonium* were reported as rare by Hallegraeff & Jeffrey (1984) and they were infrequently observed in 2010 but their large size meant that they were in the top 15 genera by biovolumes. *Dactyliosolen fragilissimus* (formerly *Rhizosolenia fragilissima*) is cosmopolitan (Tomas 1996) but possibly a new record for the region (Conkright *et al.* 2002). Species from the genus *Porosira* are mostly temperate to polar in distribution (Conkright *et al.* 2002) but have been previously reported from the Indian Ocean (Tomas, 1996). Finally *Lithodesmium* has been recorded once from the Tasman Sea (Conkright *et al.* 2002), widely from the Philippine Sea Bantu Sea and other warm water regions (Tomas, 1996). It is not clear whether the apparent changes in abundance of these genera represent significant changes in the phytoplankton community within this region or have some other cause(s). Based upon the limited spatial and temporal sampling conducted to date we can only hypothesize based on principles why the abundance of some diatom species in the Kimberley region were much greater relative to samples from Northwest Shelf to the Gulf of Carpentaria (e.g. Hallegraeff & Jeffrey 1984).

The phytoplankton community near shore in the Kimberley region was much more abundant than offshore. With an average of $\sim 0.5 \mu\text{g}$ chlorophyll *a* L^{-1} it also appears more abundant than most similar regions along the west coast of Australia (Thompson *et al.* 2010) although this may reflect the limited temporal sampling. Relative to offshore it also had a significantly greater component of larger cells and these were mostly diatoms (as above). The diatoms observed in the near shore region tended to be relatively evenly distributed throughout the water column and strongly pigmented. Diatoms with a relatively homogenous vertical distribution and high in pigmentation suggest a well mixed water column with fluctuating but low average irradiance (Litchman & Klausmeier 2001). The medium size of many of these near shore diatoms could be expected to make them easy prey for many zooplankton species (Irigoien *et al.* 2000) and they may rely on rapid growth (r-selected) to escape this predation pressure (Litchman *et al.* 2007). The nutrients to support this substantial near shore phytoplankton community may be advected on to the shelf from the strong tidal exchanges (Tranter & Leech 1987), mixed vertically due to breaking internal waves or some other mechanism yet to be elucidated.

From the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite images there were small blooms of coccolithophorids (haptophytes) present during the 2010 cruise. A number of coccolith bearing species have been previously reported from the region although their abundance was only quantified as between 1 and 100% of the total phytoplankton biomass (Hallegraeff & Jeffrey 1984). Based on pigments during the 2010 research voyage coccolithophorids were approximately 20% of the total phytoplankton biomass,

most abundant at the shelf break and they were relatively deep in the euphotic zone. The coccolithophorid blooms that are frequently reported across this region from the Kimberley to Cape York (e.g. Brown & Yoder 1994) are important on a global scale yet we know almost nothing about the ecology of these species in this region or the impacts of these blooms. Given the role these taxa play in the global carbon cycle this is a serious gap in our understanding of the carbon budget and potential acidification of the Australian environment. Samples from 2010 are being examined at greater magnification (to identify and enumerate the coccolithophorids).

Cryptophytes are rarely observed in phytoplankton samples yet their marker pigment, alloxanthin, is often found (Schulter & Mohlenberg 2003). In the Kimberley region cryptophytes were common in the phytoplankton relative to other samples from west Australia (e.g. Thompson *et al.* 2010). The mixotrophic ciliate, *Mesodinium rubrum*, which contains plastids derived from cryptophytes (Taylor & Blackburn 1970) was spatially heterogeneous but abundant overall. *M. rubrum* has an exceptional swimming speed of $\sim 7 \text{ mm S}^{-1}$ (Lindholm 1985) or an order of magnitude faster than most dinoflagellates. This speed gives it a unique capacity to move vertically reducing predation (Jonsson & Tisleius 1990), to utilize ephemeral nutrient patches and maximize irradiance. The dinoflagellate *Dinophysis miles* was also patchy in its distribution and its orange, rather than red, fluorescence indicated biliprotein pigments. It would appear that *D. miles*, like its better studied congeners *D. acuminata*, *D. caudate*, *D. fortii*, *D. infundibulus*, is consuming *M. rubrum* (Parke *et al.* 2010). The orange fluorescing plastids in *D. miles* are proposed to be obtained from *M. rubrum* but originally derived from cryptophytes and to contain both biliproteins and alloxanthin. This mode of mixotrophy provides some additional niche diversity and seems to be more common feature of phytoplankton found in the relatively stability of tropical ecosystems (Troost *et al.* 2005a, Troost *et al.* 2005b).

The phytoplankton of this region are likely to be limited by the availability of nitrogen (Elser *et al.* 2007). *Trichodesmium* is the source of 50% the nitrogen used by phytoplankton in the global ocean (Mahaffey *et al.* 2005). *Trichodesmium* is an important component of the phytoplankton of the Kimberley region and is likely to be an important nitrogen source supporting the regional ecology (e.g. Furnas *et al.* 1995, Capone *et al.* 1997). In addition the effects of rising CO_2 are predicted to double the growth rate, carbon fixation and N_2 fixation by *Trichodesmium* (Hutchins *et al.* 2007; Levitan *et al.* 2007). Thus *Trichodesmium* is likely to be even more important in the future acidified ocean and there is significant need for more attention to be focused on this pathway of N input to the Australian ecosystem.

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Potential effects of *Lyngbya majuscula* blooms on benthic invertebrate diversity and shorebird foraging ecology at Roebuck Bay, Western Australia: preliminary results

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Abstract

Nutrient enrichment can significantly alter biodiversity, producing shifts in assemblages of primary producers and favouring, for example, cyanobacterium blooms. These variations in the assemblage of primary producers consequently affect the primary consumers that depend on them. However, the consequences of these blooms for higher trophic levels are still unclear. Roebuck Bay, in the west Kimberley region is one of the main non-breeding areas for migratory shorebirds in Australia. The bay is characterised by an extremely high diversity and biomass of benthic invertebrates, which places this tropical intertidal area among the richest mudflats in the world, and it is likely that this rich benthic fauna supports the shorebird populations. Recent studies in Roebuck Bay have detected nutrient enrichment, with increasing frequency of cyanobacteria blooms. Here we present the preliminary results of the potential effects that *Lyngbya majuscula* (cyanobacterium) blooms have on the benthic invertebrate diversity and shorebird foraging ecology at Roebuck Bay. A site where *Lyngbya majuscula* was present showed a significant diminution in the diversity of benthic invertebrates relative to areas without a bloom. Also, although there was no apparent *Lyngbya*-induced change in the main prey of Bar-tailed Godwits *Limosa lapponica*, there was a change in the foraging behaviour of godwits in the area affected by *Lyngbya*, which appears to relate to a shift in diet. Nevertheless, although we found a correlation between *Lyngbya* presence and shifts in invertebrate assemblages, further work is required to confirm our findings.

Keywords: *Lyngbya majuscula* blooms, benthic invertebrate, shorebirds, Roebuck Bay, Kimberley

Introduction

A major challenge in ecology and conservation research is to improve our understanding of ecosystem diversity and function to develop proper protection, monitoring and management programs that assure their existence for future generations. Coastal ecosystems are heterogeneous, often being characterised by high levels of production (Borges *et al.* 2006) and an immense diversity of ecological processes (Constanza *et al.* 1993). However, coastal habitats are also subjected to high anthropogenic pressure, and as a result they represent the most endangered ecosystems in the world (Duarte 2007). More than one third of the human population lives on the coast and consequently between 30% and 50% of the world's principal coastal areas have been degraded in the last three decades (Duarte 2007). Determination of the effects that human activities have on these ecosystems is of primary importance since overharvesting of marine organisms, land reclamation and more recently, nutrient loading and climate change are pervasively changing coastal wetland ecosystems

throughout the world (Vitousek *et al.* 1997; Edgar *et al.* 2000).

Anthropogenic nutrient enrichment of wetlands has become a premier issue for both scientists and managers. Studies of nutrients loads on aquatic systems have determined that nutrient enrichment can significantly alter biodiversity, producing for example shifts in the assemblages of primary producers and favouring phytoplankton, cyanobacterium or macro-algal blooms that are related to episodes of anoxia and hypoxia (Cloern 2001). These variations in the assemblage of primary producers consequently affect the primary consumers that depend on them, often causing them to disappear (Valiella *et al.* 1997; Tewfik *et al.* 2005). However, the consequences of such blooms of primary producers for higher trophic levels are still unclear.

Worldwide there are less than twenty regions where large mudflats rich in shorebirds are found at low tide and only two are located in tropical regions, Roebuck Bay being one of them. Roebuck Bay, located in North-Western Australia is one of the main non-breeding areas for migratory shorebirds of the East Asia-Australasian Flyway (Bamford *et al.* 2008). The importance of Roebuck

Bay appears to relate to the elevated diversity and biomass of benthic invertebrates (the primary food source of shorebirds), which places this tropical intertidal area among the richest mudflats in the world (Rogers *et al.* 2003). The number of shorebirds using Roebuck Bay may exceed 125,000 in the non-breeding season (Rogers *et al.* 2011), making it one of the most important two shorebird sites in Australia (Rogers *et al.* 2003; Rogers *et al.* 2011). However, 20% of shorebird species that regularly migrate along the East Asian-Australasian Flyway have been officially classified as globally threatened, possibly due to land modification or habitat degradation along the flyway (Rogers *et al.* 2010). Therefore there is an urgent need to monitor and conserve the remaining important sites in the flyway. Roebuck Bay was designated as a Wetland of International Importance in 1990 under the Ramsar Convention (1971), has been recently proposed as a Marine Park, and currently ranks in the top 8 migratory shorebird non-breeding sites in the world (Rogers *et al.* 2003). It is, therefore, a highly significant bird habitat worthy of preservation at a national and international level.

Roebuck Bay is adjacent to the tourist town of Broome (15,857 inhabitants – data for 2009, Australian Bureau of Statistics. Population could double during the tourist season), and recent studies indicate a developing issue with respect to nutrient contamination. A study on regional groundwater has shown elevated nutrient levels in water originating from the area of Broome and moving into the bay (Vogwill 2003). Stable isotope studies have detected elevated $\delta^{15}\text{N}$ signature in phytoplankton and filamentous algal from the bay, indicative of nutrient

enrichment of the foodweb (A.W. Storey, UWA, unpub. data 2006). A preliminary assessment of the nutrient loads in sediments adjacent to Broome's Town Beach indicate elevated levels of P and N (Pearson 2008) and blooms of cyanobacterium (blue-green algae) *Lyngbya majuscula* first appeared during the 2005 wet season, and have increased in extent each wet season since then (de Goeij *et al.* 2008; Pearson 2008).

Here we present the preliminary results of ongoing research looking at the effects that *Lyngbya majuscula* blooms have on the benthic invertebrate diversity and shorebird foraging ecology in Roebuck Bay.

Some described effects of *Lyngbya majuscula* and other cyanobacterium on marine organisms have been attributed to the changes produce in the physicochemical and biological conditions of the habitat (*e.g.* anoxia, covering and smothering of seagrass meadows – *e.g.* Watkinson *et al.* 2005). It is expected then that *Lyngbya* blooms affect the benthic invertebrate abundance (García and Johnstone 2006) and diversity in affected areas of Roebuck Bay. Consequently *Lyngbya* blooms could reduce shorebirds' prey availability. This change of habitat conditions may have long term effects at a population level, since the loss or degradation of migratory shorebirds' habitats anywhere along their flyways is capable of precipitating a decline in their populations (Galbraith *et al.* 2002; Thomas *et al.* 2006).

Methods

Study sites

Roebuck Bay has a tropical climate, with a warm-dry season (May–November), followed by a hot-wet season (December–April). In other areas of Australia, such as Moreton Bay, nutrient inputs together with high temperatures, light conditions and iron availability drive *Lyngbya* blooms (Albert *et al.* 2005; Ahern *et al.* 2008; Johnstone *et al.* 2010). *Lyngbya* blooms occur in the wet season each year in the bay (G. Pearson and A.W. Storey personal observations), which appears to indicate that nutrient inputs, result of rainfall run-off that occurs in the wet season, drive *Lyngbya* blooms together with high water temperatures. In line with this, two sampling programs were carried out, one at the end of the dry season (November 2009) before any bloom was evident, and another mid wet season (February 2010) when *Lyngbya majuscula* was present in the bay.

The study was carried out at three locations. Sites were selected in intertidal areas to characterize: (1) an area potentially affected by wastewater treatment plant/urban activities, presenting a high density of *Lyngbya* throughout the wet season (Town Beach, TB), (2) an area located in the mouth of a tidal creek potentially affected by wet season runoff from pastoral land (One Tree, OT), and (3) an area situated in the proximity of an extensive mangrove area and away from obvious nutrient sources (south of Crab Creek, SCC) (Fig. 1).

Town Beach site is characterized by sandy sediments (Pepping *et al.* 1999; Piersma *et al.* 2006), the existence of seagrass meadows and a narrow fringe of mangroves. It is a zone used by the community as a recreational area. The other two sites, One Tree and south of Crab Creek

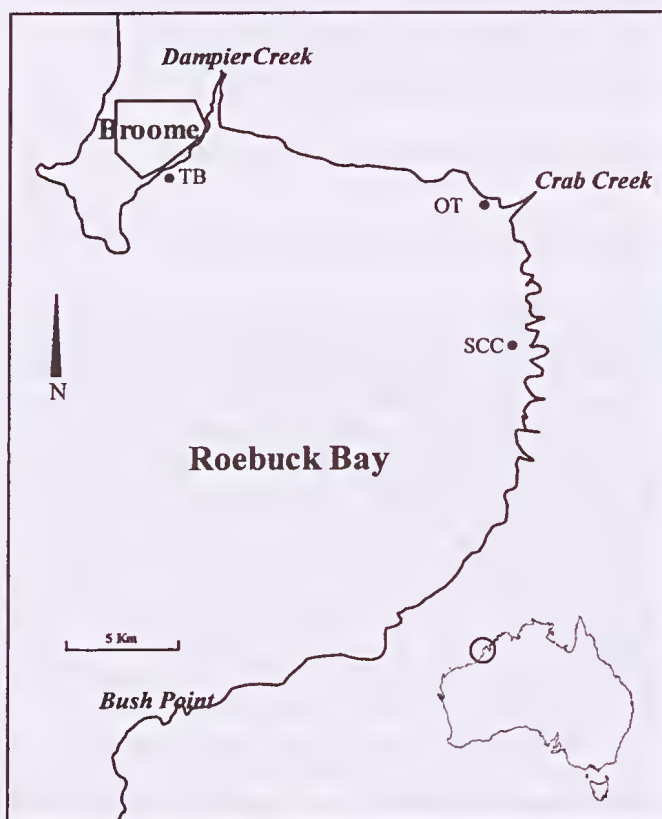


Figure 1. Map of Roebuck Bay, in North Western Australia, with the study sites indicated as TB (Town Beach), OT (One Tree) and SCC (south of Crab Creek).

are characterised by muddy sediments (Pepping *et al.* 1999, Piersma *et al.* 2006) and a wider fringe of mangal. The use of One Tree as recreational area is more restricted and the mud flats south of Crab Creek are seldom visited by humans, as they can only be accessed by boat at high tide.

Benthic invertebrate diversity and abundance

To evaluate whether the diversity and abundance of benthic invertebrates varied between the end of the dry season and mid wet season, when *Lyngbya majuscula* occurred at high densities at Town Beach, samples of benthic invertebrates were taken from the three locations indicated above in November 2009 and February 2010.

We followed the methodology used in the Monitoring Roebuck Bay Benthos program (MONROEB, de Goeij *et al.* 2003, de Goeij *et al.* 2008) which has been used in the bay for the last 14 years. Two stations were defined at each site, one 150 m offshore and the second 250 m offshore, perpendicular to the coast. At each station four samples were taken, each one consisting of six 10.3 cm diameter cores, driven 20 cm into the sediment. Therefore each sample represented a sample surface of 0.05 m² and each station represented a sampled surface of 0.2 m².

The samples were sieved on the shore initially with a 1 mm sieve to remove most of the coarser sediment and then through a 0.5 mm sieve. The samples were labelled and preserved in 70% ethanol and returned to the laboratory for processing. All samples were processed using a stereomicroscope (10 to 22 X magnification), removing all individuals, identifying to family level, and recording abundance of each family.

The information gathered from both stations in each site was pooled together following de Goeij *et al.* 2003, where the authors compared the abundance and diversity of benthic species between both stations in two sampling sites of Roebuck Bay and obtained similar results. Diversity was determined using the Shannon-Wiener diversity index.

Shorebird foraging behaviour and prey

To evaluate any differences in shorebird foraging behaviour between the end of the dry season and mid wet season, when *Lyngbya majuscula* occurred at high densities in Town Beach, observations of Bar-tailed Godwits *Limosa lapponica* chosen randomly and foraging actively were made in November 2009 and February 2010 at Town Beach and One Tree stations. Bar-tailed Godwits are long distance migrant animals and human induced changes in their non-breeding habitats could have detrimental effects at a population level, as has been proven for other long distant migratory shorebirds (Piersma 2006).

Each individual was followed during a three-minute period through a Kowa 25 x 60 telescope ($n_{Nov}^{TB} = 32$; $n_{Feb}^{TB} = 28$; $n_{Nov}^{OT} = 25$; $n_{Feb}^{OT} = 30$) three hours before and after low tide. Similar numbers of observations were taken throughout the daylight period (5–19 GMT) before and after low tide to evade the potential mudflat exposure period effect on feeding rates (Rogers and de Goeij 2006). To avoid pseudo-replication (Hulbert 1984), each new bird selected for observation was at least 20–40 m from the previous individual.

During these observations the following variables were recorded: 1) number of pecks (only the tip of the bill entered the substratum), 2) number of probes, 3) number of successful prey captures, 4) prey type (unidentified prey were excluded from diet analysis), 5) depth of probes and 6) depth of captured prey. Note that depths for (5) and (6) were recorded as one of the following three categories: i) only the tip of the bill entered the substratum, ii) less than, or half of the bill entered the substratum and iii) more than half of the bill entered the substratum. The depth of captured prey was then established in relation to the mean bill length of Bar-tailed Godwits in North Western Australia (97.4 mm for both sexes combined; Wilson *et al.* 2007). Consequently, it was considered that when only the tip of the bill entered the substratum, the prey was at a depth between 0 and 24.4 mm, when less than or half of the bill entered the substratum, the prey was at a depth between 24.5 and 48.7 mm and when more than half of the bill entered the substratum, the prey was at a depth between 48.8 and 97.4 mm.

Statistical analysis

Normality and homoscedasticity were tested (Shapiro-Wilk and Levene's test respectively) for each variable. When normality of the data was not achieved a log₁₀ (x+0.1) transformation was applied (Sokal and Rohlf 1995). The differences in abundance of invertebrates, probes per minute and prey captured per minute between months (fixed factor) and among sites (fixed factor) were analysed using a two-way ANOVA test. Differences in prey captured per minute in relation with prey depth were analysed using one-way ANOVA. When analyses showed significant differences, post-hoc tests (parametric Tukey's test) were used to determine amongst which months or sites differences existed.

Values are presented as means $\pm$ SE, unless stated otherwise. Statistical significance was set at $P \leq 0.05$. All univariate statistical tests were conducted using Statistica 7.0 (StatSoft. Inc., Tulsa, Oklahoma, USA).

Differences in the composition of the benthic invertebrate assemblage among sites with and without *Lyngbya* were explored using non-metric multidimensional scaling (nMDS) on square root transformed data, using the adjusted Bray-Curtis similarity coefficient (Clarke 1993). The statistical significance of these differences was determined by analysis of similarities (ANOSIM; Clarke 1993). All multivariate analyses were conducted using PRIMER v6 (PRIMER-E Ltd., Lutton, Ivybridge, UK).

Results

Benthic invertebrate diversity and abundance

A total of 1057 and 3389 benthic invertebrates were collected in November 2009 and February 2010 respectively. Of these, 11 main invertebrate taxa were identified. Polychaete worms compromised more than 30% and bivalves more than 20% of the total fauna in November. In February more than 40% of the fauna were sipunculids and almost 24% were gastropods. The total abundance of macrobenthos in November was 1602.5,

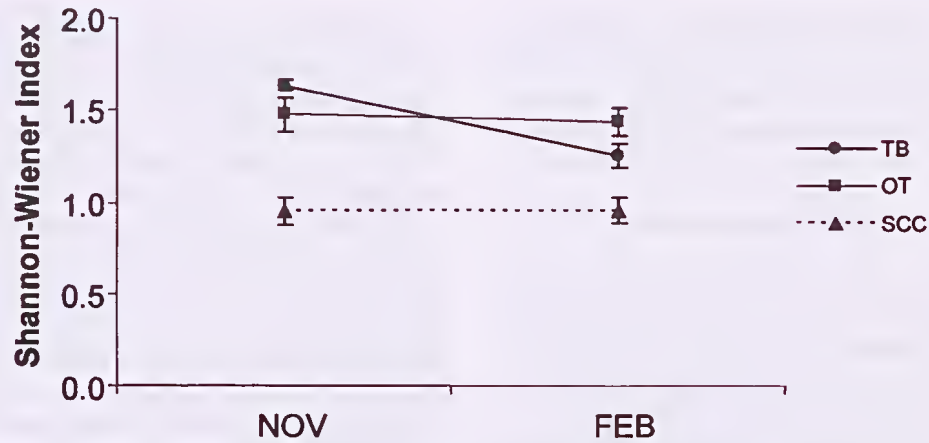


Figure 2. Mean values ($\pm$ SE) of the Shannon-Wiener diversity index for benthic invertebrates in Town Beach (TB), One Tree (OT) and south of Crab Creek (SCC) in Roebuck Bay, North Western Australia in November 2009 and February 2010.

650.0 and 67.2 individuals per m^2 for Town Beach, One Tree and south of Crab Creek respectively. In February the total abundance was 5117.5, 1437.5 and 88.4 individuals per m^2 for Town Beach, One Tree and south of Crab Creek respectively.

Diversity of invertebrates was significantly different among sites (two-way ANOVA: $F_1 = 5.6$ $P < 0.05$), between months (two-way ANOVA: $F_2 = 35.0$ $P < 0.0001$) and also among sites $\times$ months (two-way ANOVA: $F_2 = 4.6$ $P < 0.05$). Diversity of invertebrates was significantly lower at the station south of Crab Creek than in the other two stations in November and February (Fig. 2). There were no changes in invertebrate diversity between November and February in One Tree and south of Crab

Creek, but there was a significant decline in diversity in Town Beach from November to February (Fig. 2).

There were significant differences among sites for all the taxa studied (Table 1). Polychaetes, tanaids, ostracods, ophiurids (brittle stars) and isopods were significantly more abundant in Town Beach than in the other two stations (Table 1, Figures 3a, 3b, 3c, 3d, 3e). Bivalve abundance was lower south of Crab Creek in both months (Table 2, Fig. 3f). The abundance of scaphopods was higher in One Tree than in the other two stations (Table 2, Fig. 3g).

There were significant differences in polychaete, brittle star, gastropod and sipunculid abundance between November and February (Table 1). There was a

Table 1

Table 1: Differences in the mean abundance of invertebrates between November 2009 and February 2010 in Town Beach, One Tree and south of Crab Creek in Roebuck Bay, North Western Australia. Asterisks indicate differences between months, among sites or among sites $\times$ months (*: $p < 0.05$; **: $p < 0.001$; ***: $p < 0.0001$; n.s.: non-significant).

Taxa	Site		Month		Site $\times$ Month	
	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>
Polychaeta	25.97	***	45.91	***	0.69	n.s.
Crabs	5.16	**	0.85	n.s.	0.37	n.s.
Bivalves	29.22	***	0.76	n.s.	0.49	n.s.
Gastropods	9.38	***	3.77	***	3.79	***
Amphipods	9.44	***	0.69	n.s.	24.59	***
Ophiurids	34.54	***	12.65	***	4.03	*
Ostracods	10.29	***	0.40	n.s.	0.67	n.s.
Isopods	8.50	***	1.08	n.s.	1.08	n.s.
Sipunculids	73.07	***	126.69	***	73.07	***
Tanaids	55.93	***	0.26	n.s.	0.26	n.s.
Scaphopods	7.87	**	0.59	n.s.	0.65	n.s.

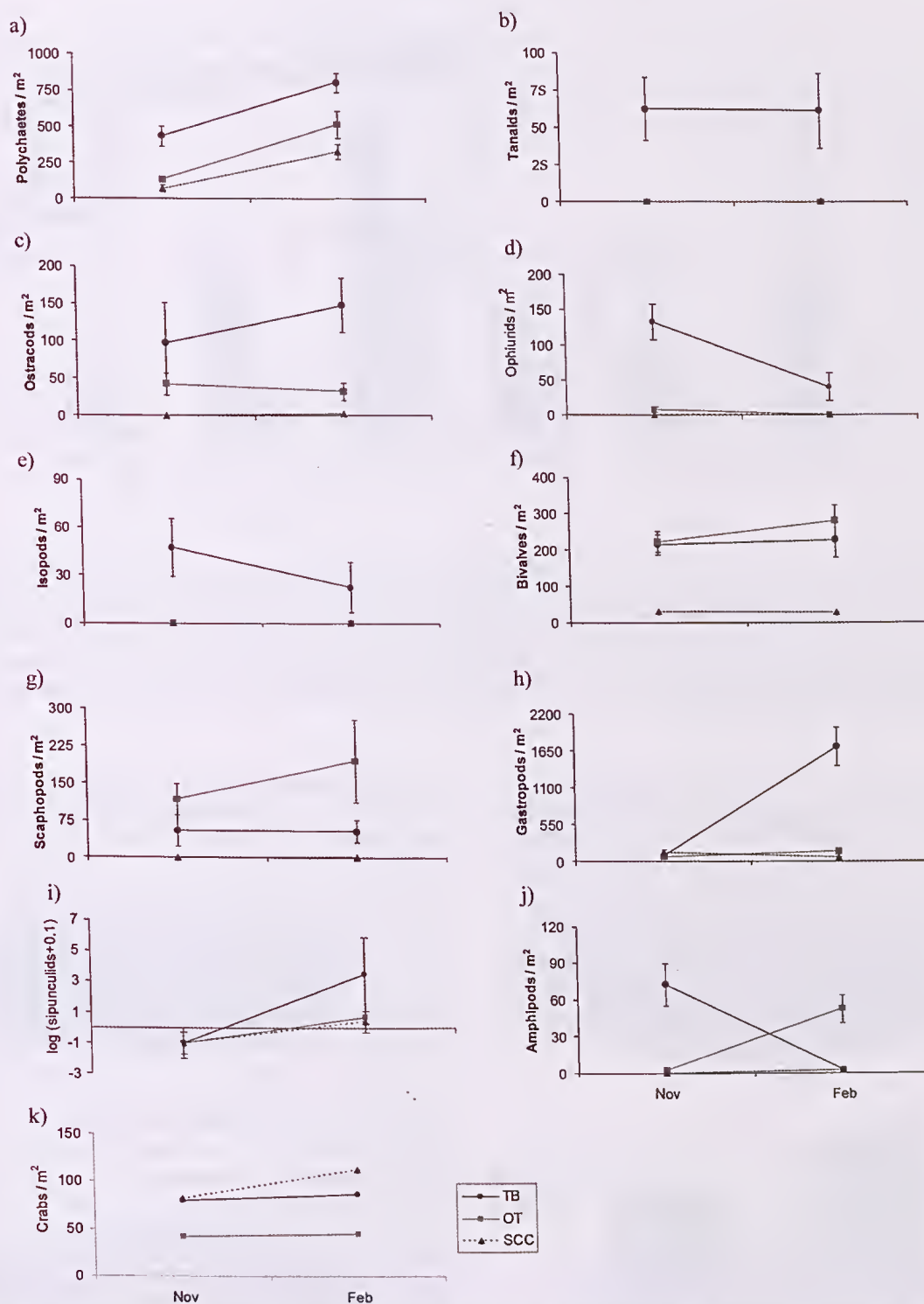


Figure 3. Mean abundance ($\pm$ SE) of benthic invertebrate taxa grouped as a) polychaetes, b) tanaiids, c) ostracods, d) brittle stars, e) isopods, f) bivalves, g) scaphopods, h) gastropods, i) sipunculids (as $\log (v+0.1)$), j) Amphipods and k) crabs in Town Beach (TB), One Tree (OT) and south of Crab Creek (SCC) in Roebuck Bay, North Western Australia, in November 2009 and February 2010.

Table 2

Table 2: Differences in the number of probes per minute and prey captured per minute by Bar-tailed Godwits *Limosa lapponica* in Town Beach and One Tree between November 2009 and February 2010 in Roebuck Bay, North Western Australia. Asterisks indicate differences between months, among sites or among sites x months (*: $p < 0.01$; **: $p < 0.001$; ***: $p < 0.0001$; n.s.: non-significant).

	Site		Month		Site x Month	
	F	p	F	p	F	p
Probes / min	9.32	**	89.61	***	5.66	*
Prey / min	105.63	***	31.35	***	3.28	n.s.

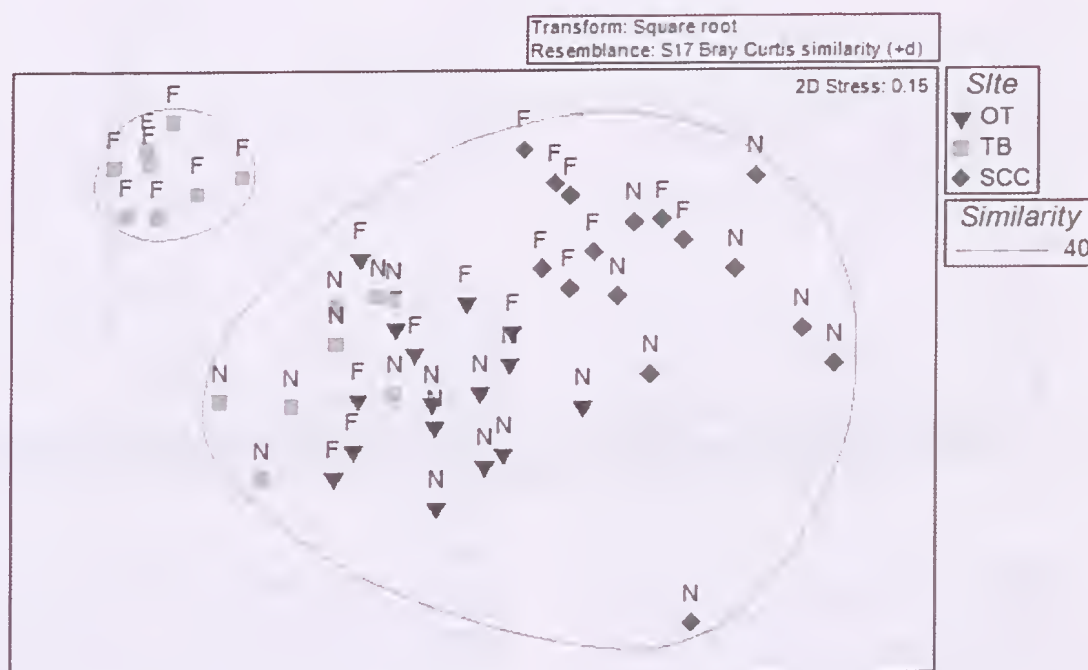


Figure 4. n-MDS ordinations using the adjusted Bray-Curtis similarity measure on square root transformed abundance data from core samples collected in Town Beach (TB), One Tree (OT) and south of Crab Creek (SCC) in Roebuck Bay, North Western Australia, in November 2009 (N) and February 2010 (F).

significant increase in the abundance of polychaetes in all the stations from November to February (Fig. 3a). There was also a significant increase in the abundance of gastropods and sipunculids at Town Beach between November and February; the abundance of both taxa was significantly higher in Town Beach in February than it was at the other stations at any time (Table 1, Figures 3h, 3i). In contrast there was a decrease in amphipods between November and February in Town Beach; the abundance of amphipods in Town Beach in November

was significantly higher than in all other samples except in One Tree in February, whereas the abundance of amphipods was also high (Table 1, Fig. 3j). There was a decrease in brittle stars between November and February in Town Beach. The abundance of brittle stars in Town Beach in November was significantly higher than in all other samples, whereas in February the abundance of brittle stars in Town Beach was similar to the abundance of brittle stars in One Tree in November (Table 1, Fig. 3d). There was no significant change in abundance of crabs at any site between both months (Table 1, Fig. 3k).

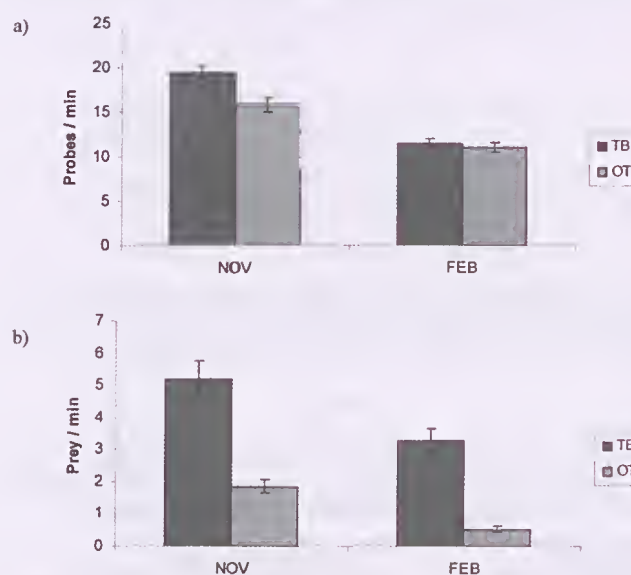


Figure 5. Mean ($\pm$ SE) number of probes and prey capture per minute of Bar-tailed Godwit feeding on benthic invertebrates in Town Beach (TB) and One Tree (OT) in Roebuck Bay, North Western Australia, in November 2009 and February 2010.

Ordination analysis of the benthic invertebrate abundance data showed that Town Beach samples from February grouped together in a distinct and coherent group separate from the rest of the samples of Town Beach sampled in November and the samples of One Tree and south of Crab Creek sampled in November and February (Fig. 4). The ANOSIM test also showed that there was a significant difference among the sites with *Lyngbya* in February (Town Beach) and the sites without *Lyngbya* in February and November (Global $R = 0.64$, $P = 0.1$).

Shorebird foraging behaviour and prey

There were significant differences in the number of probes and prey captured per minute between Town Beach and One Tree and between November and February. However the number of probes per minute in Town Beach and One Tree were similar in February (Table 2 and Fig. 5a and 5b).

There were also significant differences in the number of prey captured per minute depending on the depth of captured prey in both sites in both months (Fig. 6). Godwits captured more prey when they fed on deeper-

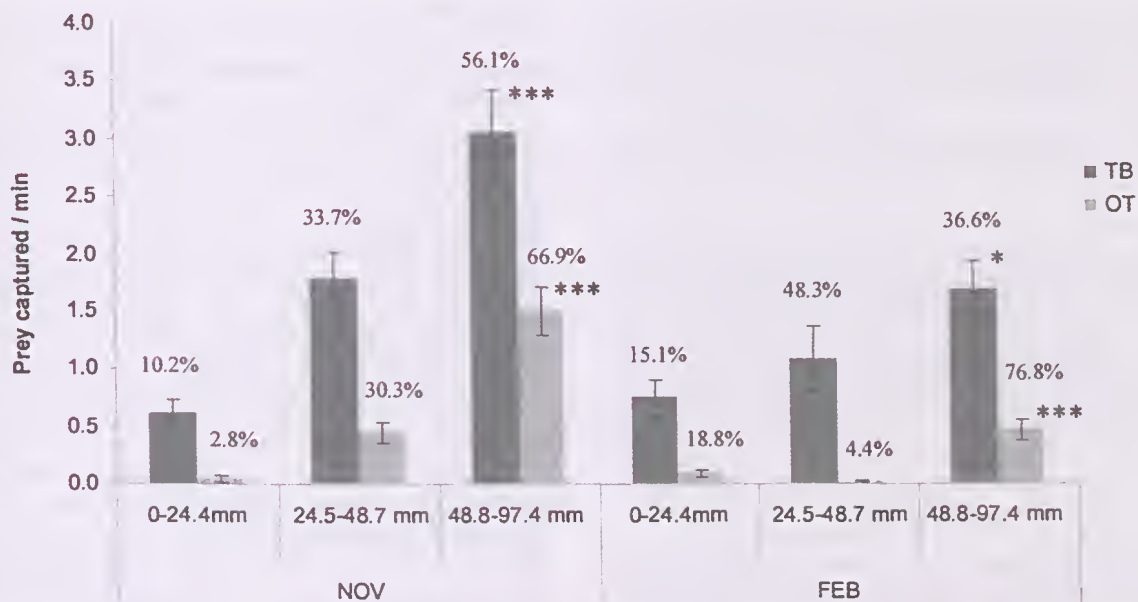


Figure 6. Mean number (±SE) of prey captured per minute by Bar-tailed Godwit depending on the depth of captured prey in Town Beach (TB) and One Tree (OT) in Roebuck Bay, North Western Australia, in November 2009 and February 2010. Asterisks indicate significant differences in the number of prey captured among the different depths in each site for each month (One-way ANOVA *: $p < 0.05$, ** $p < 0.001$, *** $p < 0.0001$). The percentage number on top of each bar indicates the percentage of prey captured at each depth in each site for each month.

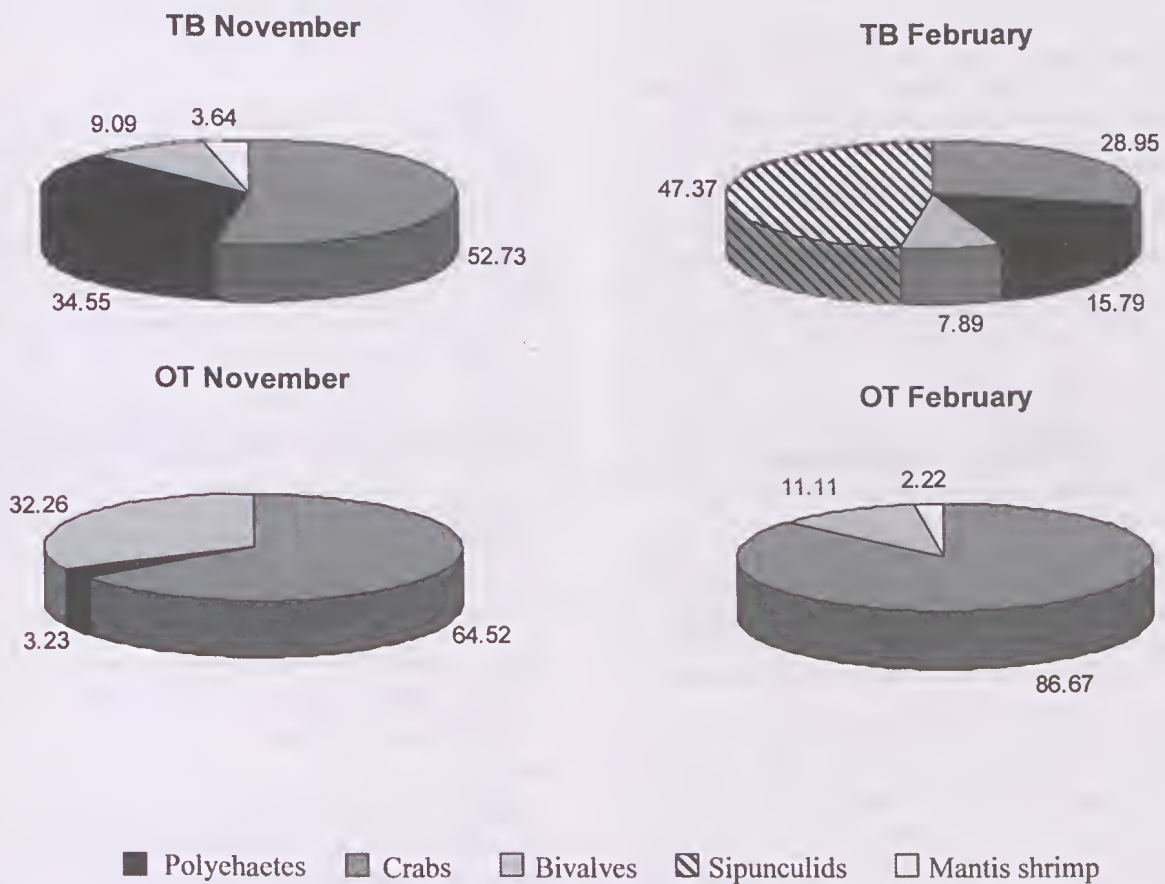


Figure 7. Percentages of the different prey captured by Bar-tailed Godwit feeding in Town Beach and in One Tree in Roebuck Bay, North Western Australia in November 2009 and February 2010. The percentages have been obtained from direct observations of Bar-tailed Godwits feeding actively three hours before and after low tide.

buried prey in both months in both stations (Fig. 6). However, although most of the prey (>55% of captured prey) were captured in the 48.8 to 97.4 mm depth category in both sites in November and in One Tree in February, in Town Beach in February 48% of the prey were captured in the 24.5 to 48.7 mm depth category (Fig. 6).

In November, the most common prey for Bar-tailed Godwits were crabs at both Town Beach and One Tree. The second most common prey were polychaetes and bivalves in Town Beach and One Tree respectively (see Fig. 7). In February, crabs were also the most common prey for godwits in One Tree, whereas in Town Beach sipunculids were most commonly taken, followed by crabs (see Fig. 7).

Discussion

Nutrient enrichment can significantly alter biodiversity, producing for example shifts in assemblages of primary producers and favouring cyanobacterium blooms which are associated with episodes of anoxia and hypoxia. Town Beach was the only site where *Lyngbya* was present in February, and it was the only site where the diversity of benthic invertebrates showed a significant decrease between November and February. This appears to be linked with the dramatic increase in abundance of sipunculids (from 0 to 3157.5 sipunculids per m²) and gastropods (from 82.5 to 1715 gastropods per m²) in Town Beach, both taxa considered as being tolerant of anoxic conditions (Langenbuch and Pörtner 2004; Vaquer-Sunyer and Duarte 2008). Also, while the community assemblage of Town Beach did not appear different to the other two sites in November, it was significantly different in February. Overall, our preliminary results suggest that *Lyngbya* blooms are affecting the benthic invertebrate community on some areas of Roebuck Bay. These results are in line with what was found in Moreton Bay (Queensland), where *Lyngbya* blooms also affected significantly the abundance of several benthic invertebrates (García and Johnstone 2006). Nevertheless changes in the distribution and abundance of benthic organisms could also be attributed to natural seasonal patterns. For example, the changes observed in the abundance of polychaetes appear to be more related to expected seasonal variation in a tropical tidal flat, where higher densities occur in the wet season (Metcalf and Glasby 2008).

Therefore, a more detailed benthic sampling program with more sampling events, including environmental variables such as nutrient concentrations and sediment grain size as well as better taxonomic resolution is required in order to provide a more precise conclusion.

Apart from observed changes in polychaetes, there were no significant changes in the abundance of the other two main Bar-tailed Godwit prey items. Although there was no apparent *Lyngbya* induced change in prey of godwits, there was a change in godwit foraging behaviour in Town Beach from November to February. In November in both sites and in February in One Tree, Bar-tailed Godwits captured most of their prey at the maximum depth range and fed mostly on crabs. Yet in February in Town Beach when *Lyngbya* was present

almost 50% of Bar-tailed Godwit prey was captured at a depth between 24.5 and 48.7 mm, and sipunculids were the main prey item. Sentinel crabs, the most abundant crab in the tidal flats of Roebuck Bay (de Goeij *et al.* 2003; de Goeij *et al.* 2008; Piersma *et al.* 2006) probably hide in their borrows at a higher depth than sipunculids, found in Town Beach only in the first centimetres of the sediment (SME personal observations). As in other situations, this change in behaviour suggests that godwits used an opportunistic foraging strategy (Davis and Smith 2001; Skagen 2006) to exploit the available, high density and low mobile sipunculids. However the implications of this shift in prey on this long distance migratory bird with high energetic demands need to be studied in depth to fully understand the potential impacts of *Lyngbya* presence on shorebirds. For example, if sipunculids have a lower energetic value per individual than more profitable prey items (*i.e.* crabs and polychaetes) this may affect the ability of birds to accumulate energy reserves. Also, the fact that godwits capture more prey per minute in Town Beach than in One Tree does not mean that the actual energy intakes are higher at Town Beach. Shorebirds can achieve higher intake rates in sites where they capture fewer but more profitable prey (Rogers and de Goeij 2006).

Finally based on these initial results a more in depth study is currently underway, involving more sampling occasions, using stable isotopes analysis, mapping *Lyngbya* extension and assessing nutrient concentrations in sediments to better elucidate the effects of *Lyngbya* blooms on benthic fauna, shorebird foodwebs and possible relationships with nutrient sources.

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Natural variability of macro-zooplankton and larval fishes off the Kimberley, north-western Australia: Preliminary findings

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Abstract

During the austral autumn, spatial (regional cross-shelf) and temporal (tidal cycle and spring-neap cycle) variability of macro-zooplankton and larval fishes off the Kimberley coast were examined in conjunction with the physical oceanography. Though surface waters were isothermal across the study area, strong stratification was evident and warm, high salinity surface waters overlaid a cooler, less saline water mass. There was no evidence of frontal features over the shelf or at the shelf break. Variability of macro-zooplankton, particularly krill and larval fishes, was defined by significant cross-shelf structuring in relation to isobath; higher concentrations were recorded for coastal waters, compared to shelf and oceanic waters. *Pseudeuphausia latifrons* was the dominant krill species in shelf waters, whereas the more speciose oceanic assemblages were dominated by species of the genus *Stylocheiron*. The greater diversity and concentrations of larvae of neritic teleost families for assemblages at the 50 m isobath distinguished coastal waters from those further offshore and within the more turbid waters of King Sound. Assemblages in proximity to the Lacepede Islands were also taxonomically distinct. The occurrence of larvae of commercially valuable teleost fishes, such as the Lutjanidae, Serranidae and Scombridae, in the study region is an important consideration for environmental and fisheries management. This study provides a baseline which can be used to evaluate anthropogenic disturbance to the Kimberley pelagic ecosystem.

Keywords: Macro-zooplankton, larval fishes, euphausiids, assemblages, oceanography

Introduction

The Kimberley has one of the least studied marine pelagic ecosystems off Australia and, in particular, the zooplankton is poorly known. Existing zooplankton studies for the region comprise those from Scott Reef (McKinnon *et al.* 2003) and the southern north-west shelf (NWS) (Wilson *et al.* 2003a; 2003b). A recent review of larval fish studies off Western Australia highlighted the absence of published work for the Kimberley region (Beckley *et al.* 2009) though an early study by Young *et al.* (1986) was completed off the southern NWS.

Game *et al.* (2009) noted the increasing exposure of pelagic ecosystems to anthropogenic disturbances which have the potential for significant negative impacts. Zooplankton is integral in marine food webs (Richardson 2008), for example, as a food source for baleen whales (Rennie *et al.* 2009) and whale sharks (Wilson & Newbound 2001, Jarman & Wilson 2004). The planktonic larval stage is crucial for reproductive success of many marine organisms including those with conservation significance such as corals and fishes which also have high economic value. Thus, there is an urgent need to understand the pelagic ecosystem of the Kimberley by establishing the composition and natural variability of

the zooplankton component and the key physical processes which drive this variability.

Planktonic communities are strongly influenced by physical oceanography at a range of spatial and temporal scales. In continental shelf systems around the world, physical processes, such as internal waves, tidal mixing, localised upwelling and wind-driven currents influence the distribution of water masses and their associated zooplankton (*e.g.* Botsford *et al.* 1994, Bradbury & Snellgrove 2001, McKinnon *et al.* 2003, Mackas & Coyle 2005).

Circulation of waters off the NWS, including the Kimberley, is understood to be a complex interaction between tides, wind and regional forcing by large-scale currents at the shelf break (Brink *et al.* 2007, Condie & Andrewartha 2008). The strongest influence upon circulation is by barotropic tides which are semi-diurnal and characterised by a large spring tidal range of >10 m (Holloway 1983; Cresswell & Badcock 2000; Condie & Andrewartha 2008). Tidal forcing induces an instantaneous response upon circulation and transport (Condie & Andrewartha 2008) and the influence upon zooplankton may be evident at temporal scales of hours (tidal cycle) to weeks (spring-neap cycle). Longer term transport over the inner and mid-shelf of the Kimberley is mostly controlled by wind-driven Ekman transport and there is a seasonal reversal in transport resulting from the change from the summer monsoon to winter

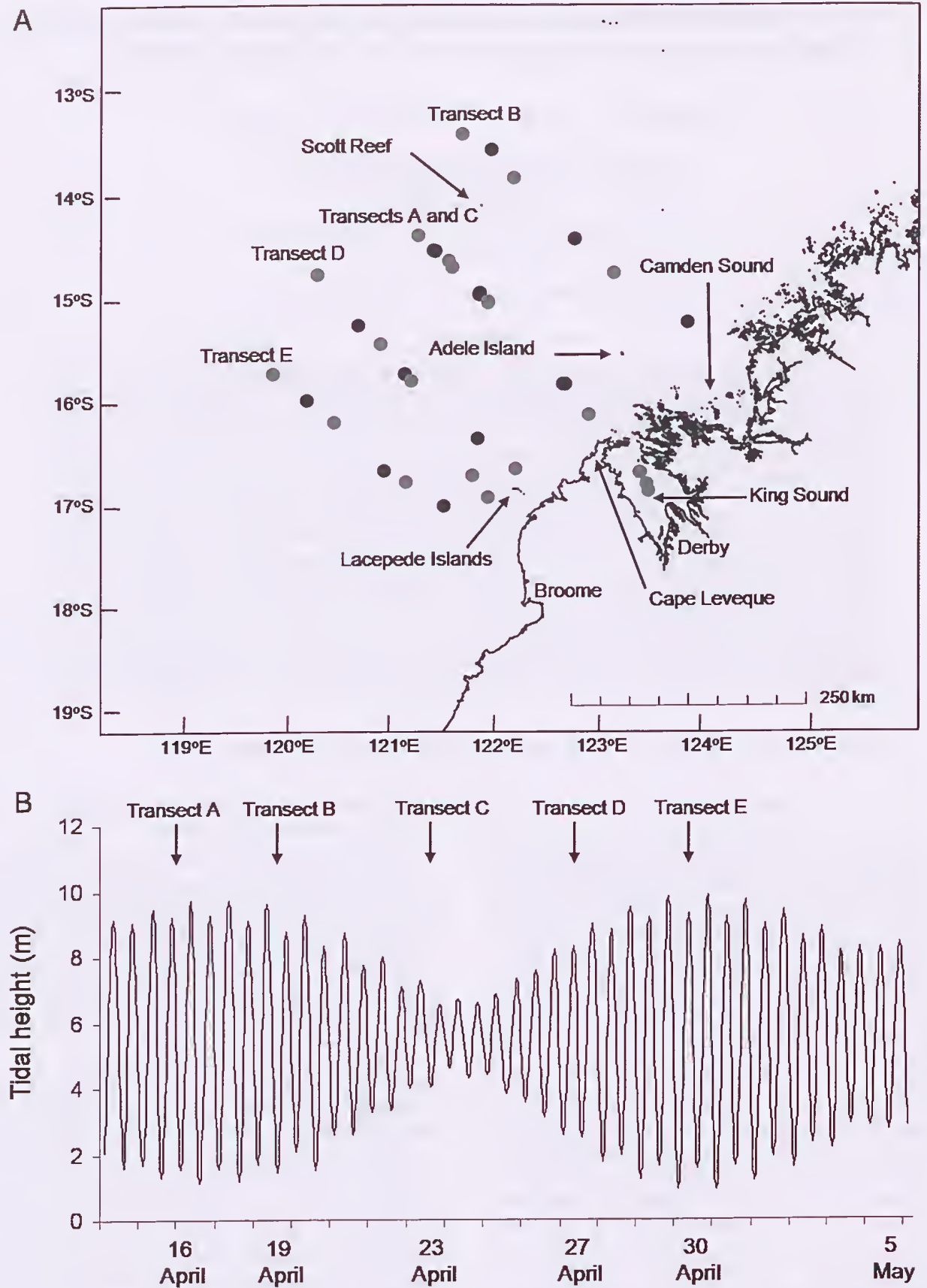


Figure 1. A) The survey area showing the location of sampling stations occupied off the Kimberley coast, north-western Australia, in April 2010. The grey-shaded circles represent stations that were occupied for 2 hours while the black-shaded circles represent sampling stations that were occupied for 12 hours over a full tidal cycle. Note: A and C represent the same transect that was surveyed during the spring (transect A) and neap (transect C) tides. B) Tidal height data for Broome corresponding with the sampling period and indicating when each transect was sampled.

south-easterly trade winds (Condie & Andrewartha 2008).

The water column of the NWS is strongly stratified in summer, characterised by a shallow mixed layer (~20 m) resulting from intense solar heating of surface and near-surface waters (Church & Craig 1998) while waters are generally well mixed during winter (Holloway & Nye 1985). Coupled with steep bathymetry and very large tidal amplitudes, the interaction of these features is known to result in the generation of strong internal waves at the shelf break (Van Gastel *et al.* 2009). It is likely that these will exert strong influence upon plankton occupying the shelf waters off the Kimberley.

This study presents the preliminary findings on the natural variability of macro-zooplankton and larval fishes in shelf and offshore waters of the Kimberley. It was conducted as part of a multidisciplinary investigation of physical forcing of productivity on the Kimberley shelf. The aim is to contribute baseline information on the zooplankton component of the pelagic ecosystem of the Kimberley.

Methods

This study was conducted from the Marine National Facility R.V. *Southern Surveyor* (voyage 03/2010) in the austral autumn over a period of 3.5 weeks (14 April to 5 May 2010). Five cross-shelf transects off the Kimberley coast which included waters in proximity to the offshore atoll, Scott Reef, were surveyed (Fig. 1). Six sampling stations were located along each transect at the 50 m (coastal), 100 m (inner shelf), 200 m (mid shelf), 500 m (outer shelf) and 1000 m and 2000 m (oceanic) isobaths. Transect lines A and C extended into King Sound adding a coastal embayment endpoint to the cross-shelf gradient. Sampling in proximity to the Lacepede Islands provided a shoreward extension of transect D. The research voyage encompassed a spring-neap cycle and transect A was sampled (14 April; new moon) during the spring tide and repeated a week later (transect C, 21 April; first quarter moon) to coincide with the neap tide (Fig. 1).

Sampling at the 2000 m, 500 m and 100 m stations and within King Sound and in proximity to the Lacepede Islands took approximately 2 hours and involved a single CTD cast and replicate plankton tows using a bongo net. To ascertain if there was net change in zooplankton between subsequent tides, the 1000 m, 200 m and 50 m stations were sampled at the start and end of a 12 hour period. The physical oceanography was examined using repeated CTD casts at approximately hourly intervals at these stations. Further, a 24 hour study was completed at a single shelf location during which the influence of tidal cycle on zooplankton was examined in detail (to be reported elsewhere).

Conductivity-temperature-depth-oxygen (CTD- O_2) measurements were performed using a Seabird SBE 19+ instrument which was equipped with dual temperature and conductivity sensors and a Chelsea TGI fluorometer. Casts were to 1000 m depth, or to ~10 m above the bottom in shallower water. These data were used to examine water masses and other physical features such as fronts which may have been present during the time of sampling.

Continuous underway measurement of the horizontal velocity along the ship's track was obtained using a vessel-mounted RDI 75 kHz Ocean Surveyor Acoustic Doppler Current Profiler (ADCP) (Teledyne RD Instruments). The instrument was set to record from just below the surface to a maximum water column depth of 300 m and data were averaged in 8 m depth bins.

Replicated depth-integrated bongo net samples (100 μ m and 355 μ m meshes, mouth area 0.196 m², diameter 0.6 m) were obtained by towing the nets obliquely to the surface from a maximum depth of 150 m (or from 10 m off the bottom in shallow water) at a ship's speed of 2 knots for 15 minutes. A mechanical General Oceanics flow meter was positioned centrally in each of the nets and they were linked electronically to a CSIRO-developed interface from which the tow profile could be monitored and the volume of seawater filtered quantified. The samples from all stations were preserved in 5% formaldehyde. For examination of macro-zooplankton, particularly krill and larval fishes, only data from the 355 μ m net are presented here.

The bio-volume, expressed as the settled volume (ml / m³ filtered seawater), of macro-zooplankton from each 355 μ m bongo net sample was determined using the standard method of George and White (1985). Settled volumes of plankton were measured (to nearest 1 ml) by pouring the samples into graduated cylinders and allowing the material to settle for 24 hrs. If necessary, detritus (pieces of macro algae) and large organisms (e.g. jellyfish) were removed prior to establishing the settled volume.

Plankton samples were sorted with the aid of a dissecting microscope. Larval fishes, squid and lobster phyllosoma were removed for later identification and the zooplankton assemblages were described in terms of their composition, i.e. major taxonomic groups. Numerical abundance of euphausiids was established using the sub-sampling method of Gibbons (1999) and counts were standardised to the number per m³ of filtered seawater. Adult and juvenile stages were identified to species level using relevant literature (Baker *et al.* 1990; Gibbons 1999; Ritz *et al.* 2003).

The counts of larval fishes were standardized to number of larvae per m³ of filtered seawater. Larval fishes were identified to family level using relevant literature (e.g. Moser & Ahlstrom 1970, Moser 1984, Olivar & Beckley 1997, Neira *et al.* 1998, Olivar & Fortuño 1991, Leis & Carson-Ewart 2000, Richards 2006).

Uni- and multivariate techniques were applied using the statistical software package SPSS 14.0 to examine spatial and temporal trends in the bio-volume of macro-zooplankton and the concentrations of larval fishes. Spatial factors included transect and isobath while temporal factors included spring and neap tides, subsequent tides and day versus night (diel). Prior to analysis, the bio-volume of macro-zooplankton and concentrations of larval fishes were $\log_{(10)}$ transformed. For all ANOVA tests Levene's test for homogeneity of variances was applied; where non-homogeneity existed in the data set, *post hoc* testing using the Games-Howell test, which assumes unequal variances, was used for pair-wise comparisons. Analyses were approached iteratively using a three-way ANOVA design to identify

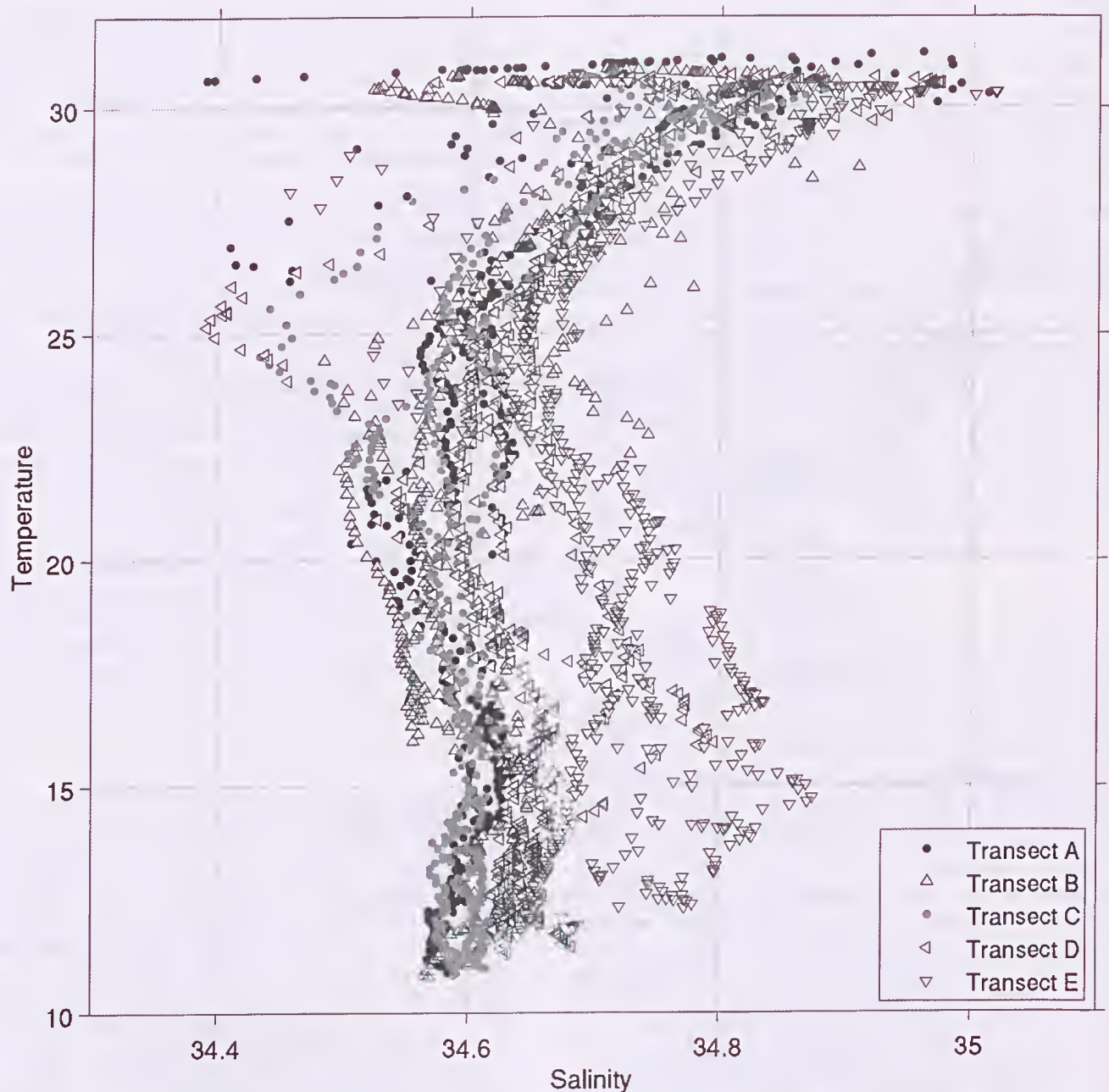


Figure 2. Temperature-salinity profiles of the upper 300 m of the water column measured over all transects off the Kimberley coast.

the factor(s) most responsible for the observed patterns. This analysis used only those samples collected at 12 hr sampling stations.

Subsequently, a one-way ANOVA was used to resolve significant differences in relation to isobath using all samples from all 2 hr and 12 hr sampling stations, including stations within King Sound and in proximity to the Lacepede Islands. Differences between spring and neap tides were examined using a two-way ANOVA (transect and isobath) for samples collected at transects A (spring tide) and C (neap tide).

Analysis of larval fish assemblage structure was undertaken using the PRIMER-6 software package (Clarke & Warwick 2005). Prior to analysis, the concentrations of larval fishes were $\log_{(x+1)}$ transformed to

reduce the weighting of dominant families and a Bray-Curtis resemblance matrix was constructed. The spatial structure of larval fish assemblages was examined using multi-dimensional scaling ordination (MDS) with samples classified according to isobath. Hypothesis testing in relation to larval fish assemblages was done iteratively and commenced using a three-factor PERMANOVA design (Anderson *et al.* 2005) applying the same format as described above. Significant results were examined *post hoc* using the analysis of similarity (ANOSIM) routine to determine where the significant differences existed. The similarity percentage routine (SIMPER) routine was applied to identify the taxa most responsible for delineation between the different larval fish assemblages.

Results

Oceanography

Temperature-salinity (T-S) profiles of the upper 300 m of the water column for shelf and offshore waters revealed two distinct water masses; high temperature ($>30^{\circ}\text{C}$) and high salinity (>34.7 psu) surface water overlaid upon cooler, lower salinity water (Fig. 2). The T-S profile indicated that there was little spatial variability, i.e. between transects, in these properties during the sampling period. Cross-shelf sections of T and S are illustrated for transect B which extended into coastal waters at the entrance to Camden Sound. This showed that, vertically, the upper water column (to ~ 60 m depth) was strongly isothermal (Fig. 3A). The warm, high salinity water mass was present from the shelf break (~ 200 m) to the inner shelf but there was some evidence of lower salinity coastal water (Fig. 3B). The salinity of

shelf water was higher by 0.3 psu, but up to 0.6°C cooler, compared with waters occupying the same depths further offshore and this may represent evaporative cooling over the broad shallow shelf. There appeared to be no obvious frontal features over the shelf or at the shelf break. Current velocities were strongest in the alongshore direction (Fig. 3C) and were, on average, 0.1 – 0.2 m s^{-1} greater than in the cross-shelf direction. Over a tidal cycle, i.e. between subsequent low tides, there was an apparent shift from a stratified water column at low tide to one that was well mixed around mid to high tide as illustrated by an inner shelf station along transect C (Fig. 4).

Macro-zooplankton

The mean bio-volume of macro-zooplankton (settled volume ml m^{-3}) showed a decreasing trend from coastal to oceanic waters although there was some spatial variability (Fig. 5). Mean bio-volume of zooplankton was highest at the 50 m isobath (1.52 ml m^{-3}) and decreased offshore ($<0.4\text{ ml m}^{-3}$) (Fig. 6A). In proximity to the Lacepede Islands, mean zooplankton bio-volume was higher (0.89 ml m^{-3}) than in King Sound (0.33 ml m^{-3}).

A three-factor ANOVA revealed this cross-shelf pattern to be significant in relation to isobath and transect ($p < 0.001$) but inspection of the F-ratios indicated that

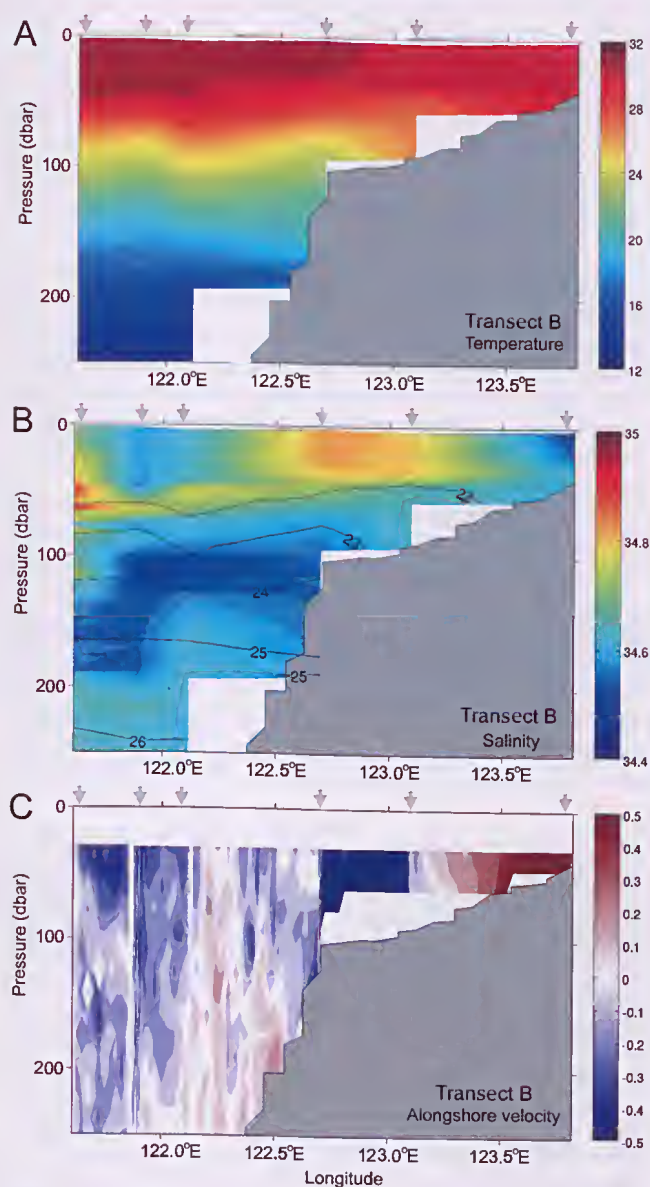


Figure 3. A) Temperature, B) salinity (density in contours) and C) alongshore velocity (blue denotes south-westward flow and red north-eastward flow) along transect B. Arrows denote CTD cast locations.

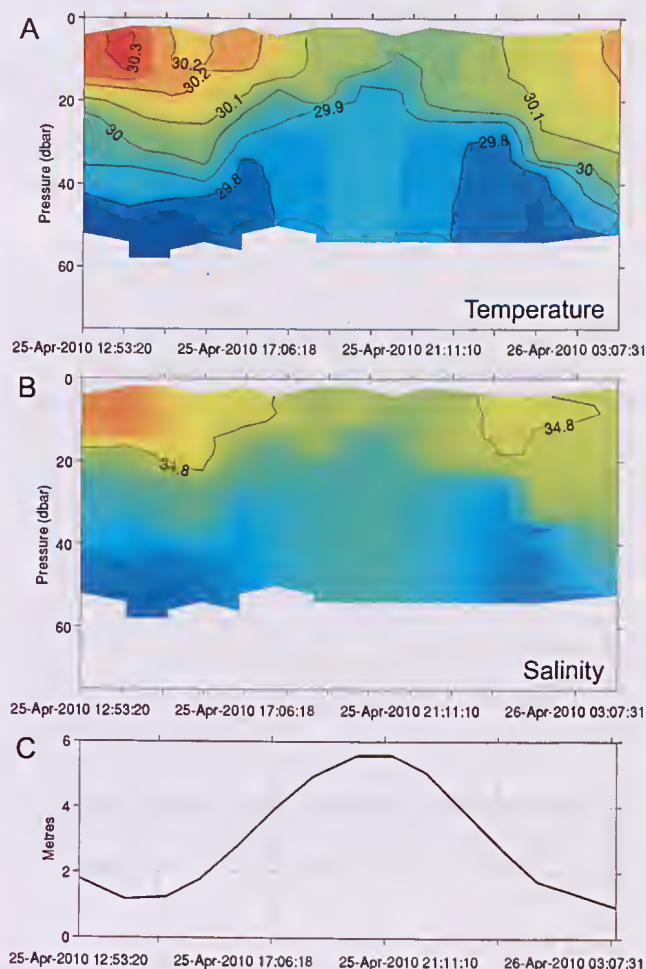


Figure 4. A) Temperature and B) salinity profiles sampled at ~ 50 m depth along transect C over a 12 hour tidal cycle. C) Tidal height at Adele Island, just north of the transect.

Table 1

Results of three-factor ANOVA which examined differences in the bio-volume of macro-zooplankton (ml settled volume / m³) in relation to the factors isobath, transect and diel variation for samples collected in shelf and oceanic waters off the Kimberley coast, north-western Australia, April 2010.

Factors	df	MS	F	p
Isobath	2	12.3	215.6	<0.001
Transect	4	0.53	9.5	<0.001
Diel	1	0.01	0.3	0.6
Isobath x Transect	8	0.42	7.3	<0.001
Isobath x Diel	2	0.1	1.8	0.18
Transect x Diel	4	0.13	2.2	0.09
Isobath x Transect x Diel	7	0.13	2.2	0.06
Residual	29			
Total	58			

isobath exerted the strongest influence (F-ratio two orders of magnitude greater than the other main effects and interactions; Table 1). One-way ANOVA showed that cross-shelf structuring was defined largely by the significantly higher ($p < 0.001$) bio-volume at the 50 m isobath (as well as in proximity to the Lacepede islands, $p < 0.01$) when compared with stations further offshore and within King Sound. Three-way ANOVA identified the influence of subsequent tides to be confounded by diel variation, although neither was significant. Two-way ANOVA showed a significant difference overall in the mean bio-volume of macro-zooplankton between spring and neap tides ($p < 0.001$). Significantly higher bio-volume corresponding with the neap tide was only recorded for the 50 m, 100 m and 200 m isobaths (Fig. 7A).

Within macro-zooplankton assemblages, copepods and euphausiids were ubiquitous across the study area though chaetognaths and sergestid shrimps (*Lucifer* spp.) were often abundant at mid and inner shelf stations. Larval cephalopods and lobster phyllosoma were recorded at both shelf and oceanic stations and the larval and post-larval stages of decapod crustaceans (mostly crab zoea), echinoderms (crinoid pluteus larvae and post-larval ophiuroids), gastropods and polychaetes were also conspicuous components of the Kimberley macro-zooplankton.

Concentrations of euphausiids (largely comprised of larval stages) were highest (6.9 / m³) at the 50 m isobath but were not recorded in coastal waters in the vicinity of the Lacepede Islands (Fig 6B). Very low concentrations (<0.1 / m³) of larval and adult stage euphausiids were recorded within King Sound. *Pseudeuphausia latifrons* was the most abundant euphausiid overall and dominated euphausiid assemblages in shelf waters while oceanic stations were dominated by species of the genus *Stylocheiron* (in particular, *S. carinatum*) and *Euphausia* species.

Larval fishes

Mean concentrations of larval fishes (number / m³ seawater) for depth-integrated bongo samples (range: 0.06 – 3.2 larvae / m³) revealed a decreasing trend from coastal to oceanic waters (Fig. 8) and significant

structuring in relation to isobath, transect and diel variation (Table 2). F-ratios showed that isobath exerted the strongest influence upon the observed pattern. As described for macro-zooplankton, the influence of subsequent tides was confounded by diel variation.

One-way ANOVA indicated that cross-shelf structuring was driven by the significantly higher concentrations of larval fishes inshore at the 50 m isobath (1.36 larvae / m³; $p < 0.001$) and in proximity to the Lacepede Islands (1.5 larvae / m³; $p < 0.01$) compared to stations further offshore and within King Sound (Fig. 6C). Instances where the concentrations of larval fishes in plankton samples were <0.1 larvae / m³, of which there were two, were associated with the presence of large jellyfish or an observably higher abundance of other planktonic predators such as chaetognaths. There was no significant difference ($p = 0.27$) in the concentrations of larval fishes between spring and neap tides (Fig. 7B).

Depth-integrated bongo sampling collected 6,513 larval fishes representing 110 teleost families and, across all transect stations, there was a high diversity of teleost families (range: 35 – 57 families; Fig. 6D). In general, the number of neritic families ($n = 90$ families) declined offshore whereas the number of oceanic meso-pelagic families decreased towards the coast. Samples from both King Sound and the Lacepede Islands contained only the larvae of neritic families and were considerably lower in diversity (14 and 22 families, respectively).

The percentage contributions of larval fishes by family for assemblages representing each isobath revealed taxonomic differences with distance offshore (Table 3). Coastal and reef-dwelling families were most abundant over the shelf and included the Gobiidae (gobies), ptereleotrine Microdesmidae (dartfishes), Lutjanidae (snappers and fusiliers), Pomacentridae (damselfishes), epinepheline Serranidae (groupers and coral trouts), Labridae (wrasses), Mullidae (goatfishes) and Scaridae (parrotfishes).

At the shelf break and offshore, there was a greater abundance of larvae of pelagic families such as the Gempylidae and Scombridae (tunas: *Katsuwonus pelamis*, *Auxis* and *Thunnus* species and mackerels: *Rastrelliger*

Table 2

Results of three-factor ANOVA which examined differences in the concentrations of larval fishes (number / m³) in relation to the factors isobath, transect and diel variation for samples collected in shelf and oceanic waters off the Kimberley coast, north-western Australia, April 2010.

Factors	df	MS	F	p
Isobath	2	13.9	80	<0.001
Transect	4	0.7	4.1	0.01
Diel	1	1.7	9.6	0.004
Isobath x Transect	8	0.08	0.47	0.8
Isobath x Diel	2	0.04	0.21	0.8
Transect x Diel	4	1.3	7.6	<0.001
Isobath x Transect x Diel	7	0.28	1.6	0.2
Residual	29			
Total	58			

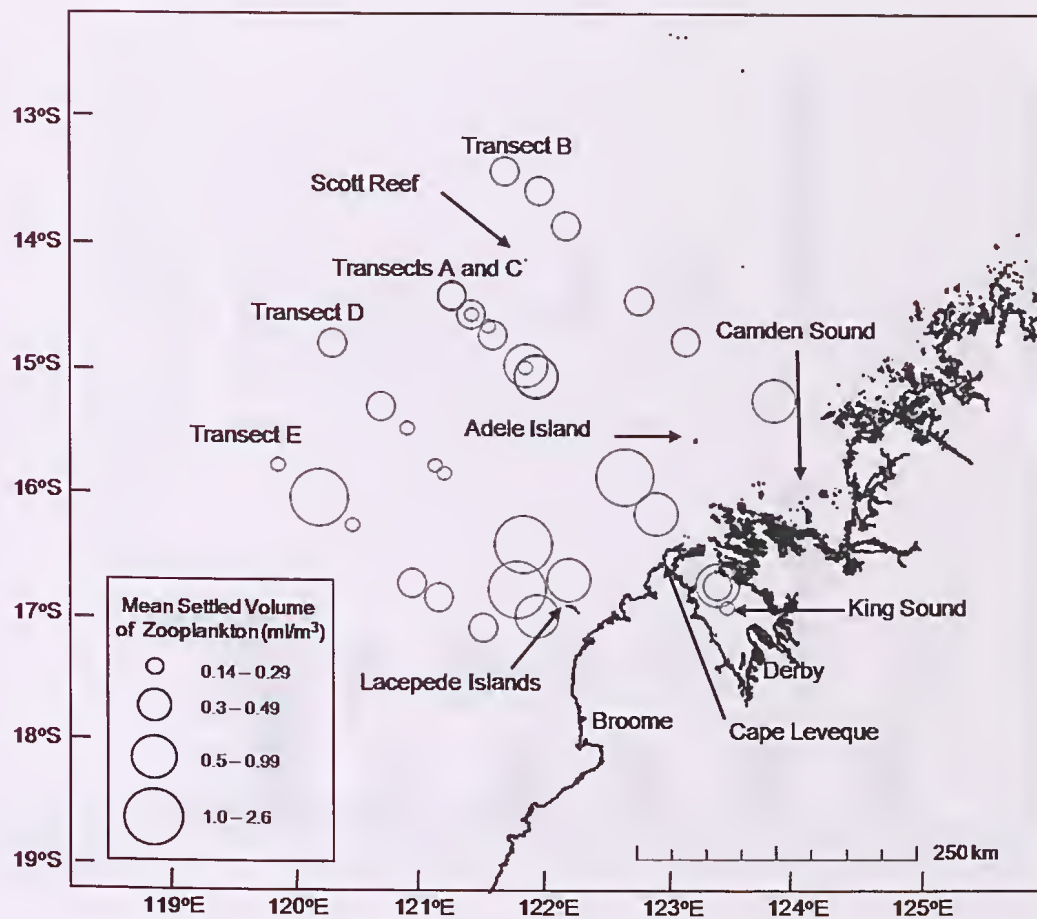


Figure 5. Mean bio-volume of macro-zooplankton (ml / m^3) sampled using a $355 \mu\text{m}$ mesh bongo net in shelf and oceanic waters off the Kimberley coast, north-western Australia, April 2010.

and *Scomberomorus* species). Myctophidae larvae were the most abundant of the meso-pelagic families and were ubiquitously distributed in oceanic and shelf waters. These larvae accounted for >35% of all larvae in assemblages at the outer shelf (200 m) and offshore but were less abundant toward the coast. In contrast, Bregmacerotidae (pelagic codlets) declined in their contribution with distance offshore. Leptocephalus larvae, in particular those of the neritic Congridae (conger eels), were a conspicuous component of the oceanic assemblage.

Multi-dimensional scaling ordination of larval fish assemblages showed clear spatial separation which defined a gradient from coastal to oceanic waters. Assemblages in coastal waters (50 m isobath), including those in proximity to the Lacepede islands, were clearly separated from assemblages at the mid and outer shelf (100 m and 200 m), shelf break (500 m) and oceanic (1000 m and 2000 m) stations (Fig. 9). The King Sound assemblage was also distinct from all other assemblages and was characterised by low diversity.

There was significant structuring of larval fish assemblages in relation to transect, isobath and diel variation as well as significant interaction between each of these terms (Table 4). Isobath exerted the strongest influence upon the observed structure as indicated by the higher value for the components of variation.

Cross-shelf structuring of larval fish assemblages was defined by the strongly significant difference between the 50 m assemblage compared to all other assemblages (Appendix 1: ANOSIM $R > 0.8$ for all pair-wise comparisons). The larval fish assemblage characterising the Lacepede Islands was also significantly different from all other assemblages. The main distinction between these two assemblages (50 m and Lacepede Islands) and those further offshore was the higher abundance of neritic larvae, particularly Bregmacerotidae, Engraulidae, Gobiidae and Nemipteridae which were generally absent further offshore, as well as fewer Myctophidae over the inner shelf. The Lacepede Island assemblage was delineated from that occurring at the 50 m isobath by the complete absence of myctophid larvae. The larval fish assemblage which characterised King Sound was also significantly different ($R > 0.7$, $p = 0.001$) from all other assemblages based on the low abundance of larvae of a few neritic families. Mid and outer shelf (100 m and 200 m) assemblages were significantly different from oceanic assemblages ($R > 0.2$, $p = 0.001$) and were defined largely by differing concentrations of the ubiquitously distributed Myctophidae larvae and larvae of some neritic families. Two-way ANOVA revealed an overall significant difference in larval fish assemblages between spring and neap tides ($R = 0.5$, $p = 0.001$), however pair-wise comparisons using one-way ANOSIM could not be conducted due to insufficient replication.

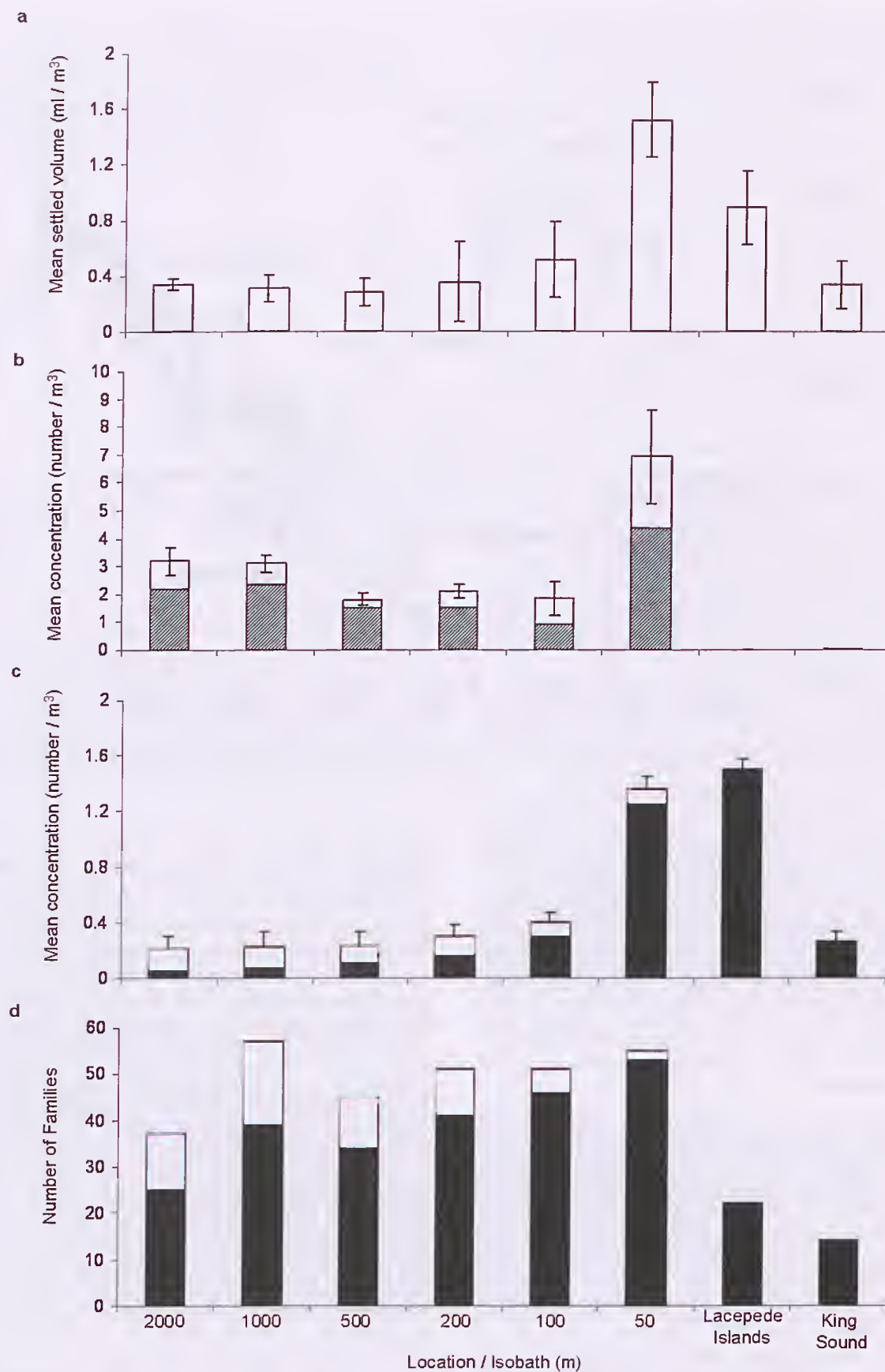


Figure 6. A) The mean bio-volume (ml / m³ seawater) of macro-zooplankton, B) mean concentrations (number / m³ seawater) of euphausiids, C) mean concentrations of larval fishes and D) total number of families of larval fishes from depth-integrated bongo samples for shelf and oceanic waters off the Kimberley, north-western Australia in April 2010. The standard errors are given for the total mean values of concentrations.

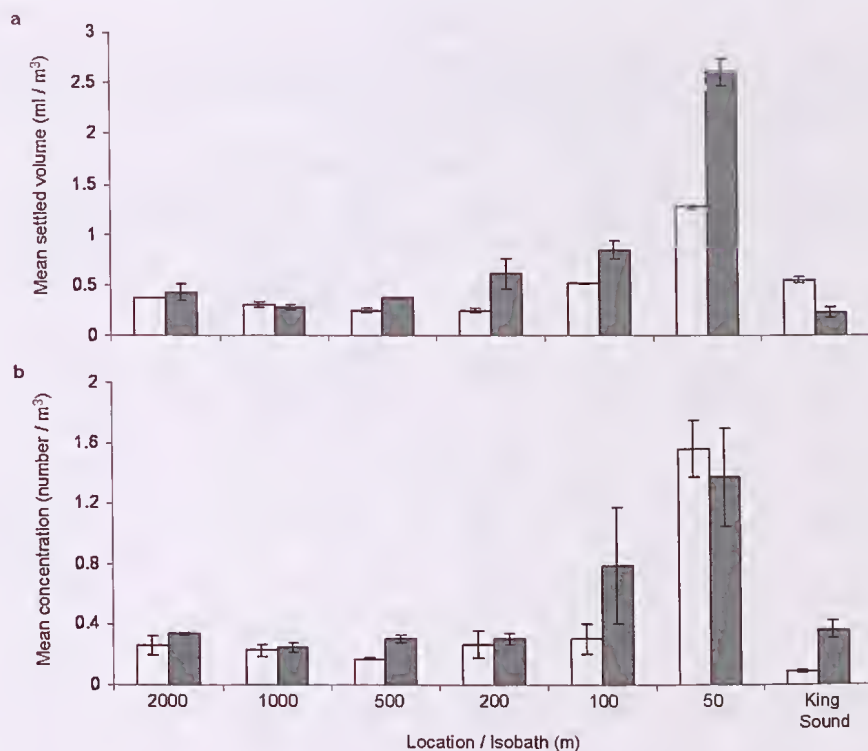


Figure 7. Comparison of A) the mean bio-volume (ml / m³ seawater) of macro-zooplankton and B) the mean concentration (number / m³ seawater) of larval fishes between spring (transect A) (white bars) and neap (transect C) (shaded bars) tides for depth-integrated bongo samples from shelf and oceanic waters off the Kimberley coast, north-western Australia in April 2010. The standard error is given for all mean values.

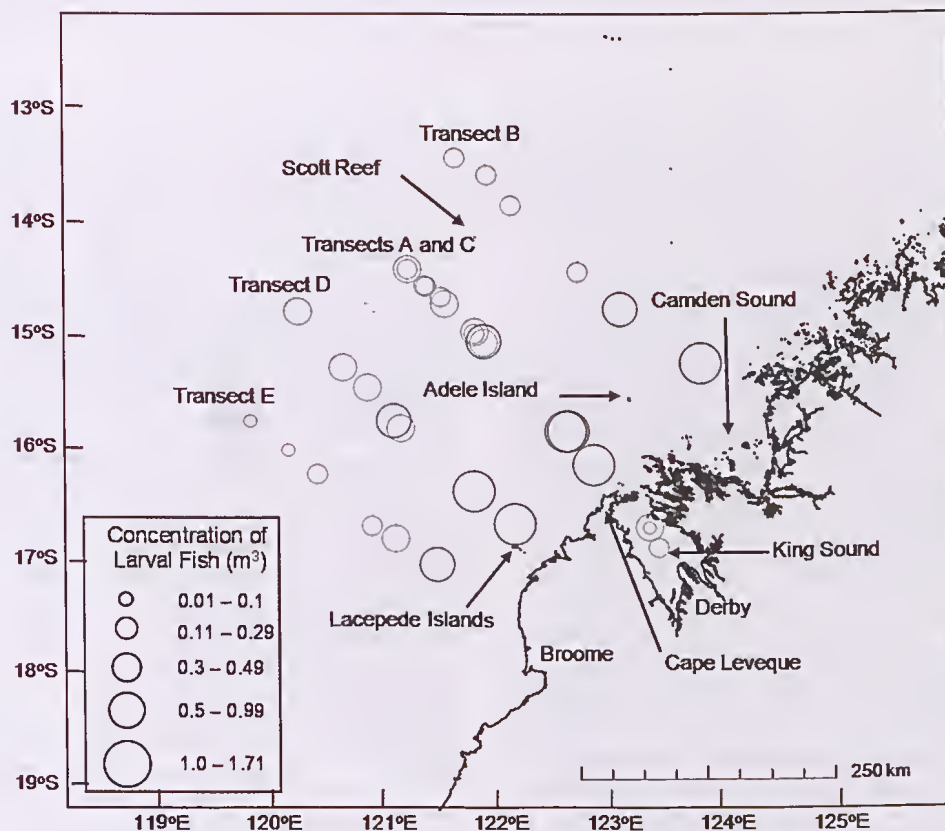


Figure 8. Mean concentration of larval fishes (number / m³) sampled using a 355 µm mesh bongo net in shelf and oceanic waters off the Kimberley coast, north-western Australia, April 2010.

Table 3

Mean percentage composition by family for larval fish assemblages across the respective isobaths off the Kimberley coast, north-western Australia. Note: only the ten most abundant families by mean concentration are shown for each isobath and spaces do not indicate absence. The superscript indicates the oceanic meso-pelagic families.

Family	Sampling Location (%)							Lacepede Islands	King Sound
	2000m	1000m	500m	200m	100m	50m			
Apogonidae					3.3	5.2		3.3	6.4
Bregmacerotidae		9.3	14.6	15.3	17.4	25.7			
Callionymidae						2.8	1.1		
Carangidae					3.6	1.9			1.5
Champsodontidae		2.4	3.1	5.3	7.9				
Congridae	2.8	2.8	6.8						
Engraulidae						15.9	49.3		
Gempylidae	2.6	2.5	2.0						
Gobiidae				2.9	6.6	15.2	32.8		27.3
Gonostomatidae ^o	8.4	8.7	4.6	2.2					
Labridae	6.1	1.9	3.1						1.1
Lutjanidae				3.9	3.2				
Microdesmidae				2.7					
Melanostomiidae ^o	1.8								
Monacanthidae						2.4	2.1		
Mugilidae									3.9
Mullidae					4.7	2.2			
Myctophidae ^o	42.0	40.4	38.5	35.9	20.1	8.1			
Nemipteridae						4.6	4.4		3.6
Paralepididae ^o				5.5	3.3				
Pempheridae									1.7
Phosychthyidae ^o	6.7	6.0	2.1						
Pinguipedidae							2.3		
Scaridae			1.5						
Sciaenidae									18.9
Scombridae	2.2	2.0		3.6					
Scopelarchidae ^o	4.7								
Scorpaenidae			2.3						
Sillaginidae									15.5
Sparidae									16.4
Sternoptychidae ^o	2.8	3.1							
Synodontidae				2.8	3.5				
Other neritic taxa	14.7	13.4	17.9	17.3	24.4	15.8	4.6		3.7
Other meso-pelagic taxa	5.2	7.6	3.4	2.4	1.8	0.1			

Discussion

The upper water column off the Kimberley coast in the austral autumn was strongly isothermal across the study area with warm, high salinity waters extending to ~60 m depth (SST >30°). A second, deeper water mass was cooler and less saline. Temperatures of the upper water column reported by Brink *et al.* (2007) for the region west of the Kimberley were several degrees cooler but they sampled in the austral winter. The TS signature of the deeper water mass was similar for the two studies. For coastal waters off the Dampier Archipelago to the south of the Kimberley, Pearce *et al.* (2003) reported similar high water temperatures in summer and autumn.

As in the current study, Brink *et al.* (2007) found no evidence of frontal features over the shelf or at the shelf break. However, Belkin *et al.* (2009) noted the seasonal evolution of regional frontal patterns over the NWS due to periodic upwelling (Holloway *et al.* 1981). In summer, numerous small-scale fronts develop which, as the season progresses, coalesce to form large-scale (hundreds of kilometres long) coherent filaments which are temporally persistent (weeks to months).

Table 4

Results of three-factor PERMANOVA which examined structuring of larval fish assemblages in relation to the factors isobath, transect and diel variation for samples collected in shelf and oceanic waters off the Kimberley coast, north-western Australia, April 2010.

Factors	df	Mean Square	Components of Variation	Pseudo-F	p
Transect	4	3970	15.9	3.9	<0.001
Isobath	2	30322	39.1	30.1	<0.001
Diel	1	5720	12.8	5.7	<0.001
Transect x Isobath	8	3756	26.8	3.7	<0.001
Transect x Diel	4	2096	14	2.1	0.002
Isobath x Diel	2	2440	12.6	2.4	0.002
Transect x Isobath x Diel	7	1591	17.1	1.6	0.009
Residual	29	1007	31.7		
Total	57				

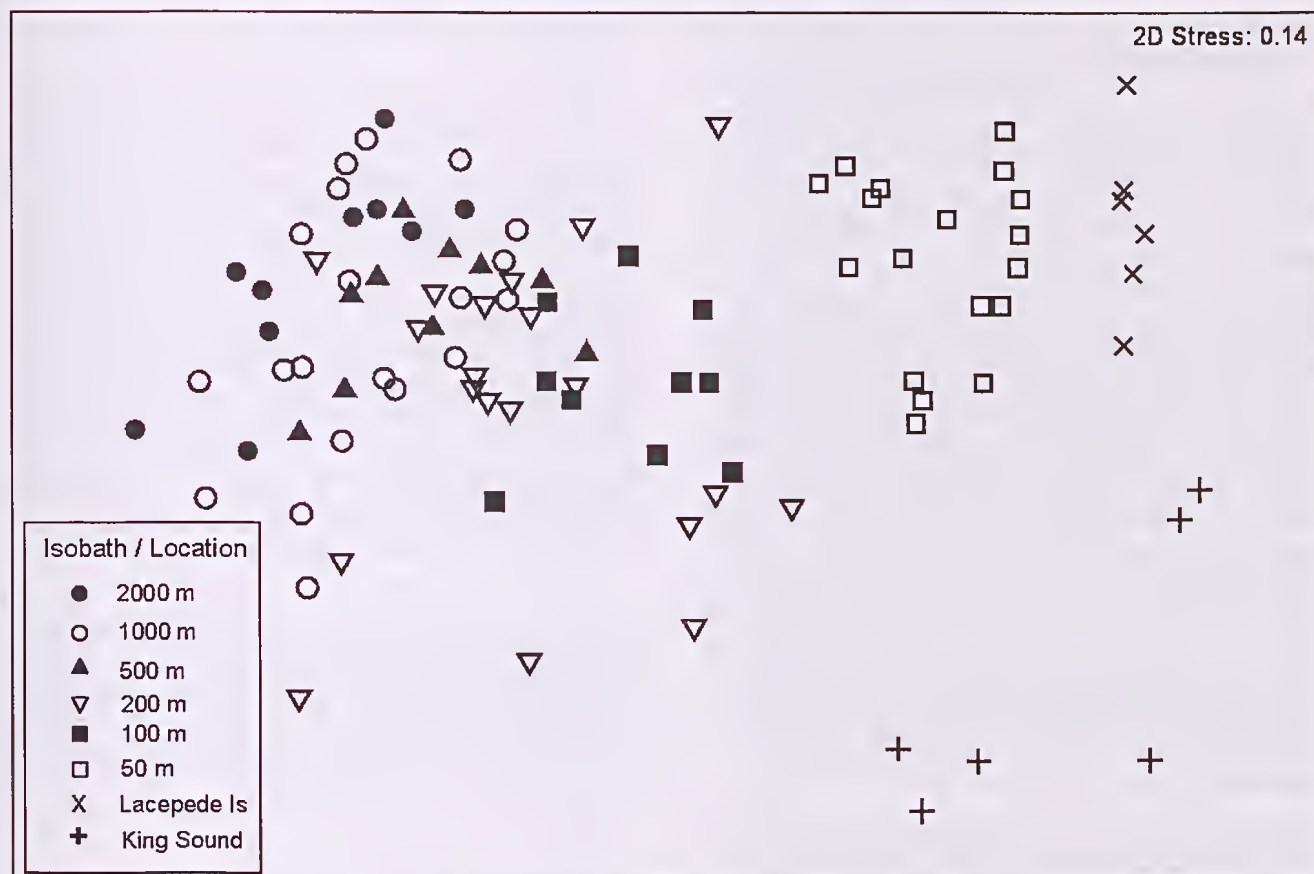


Figure 9. Multi-dimensional scaling (MDS) representation of the structuring of larval fish assemblages for all depth-integrated bongo samples in oceanic waters and over the shelf (including in proximity to the Lacepede Islands and in King Sound) off the Kimberley coast, north-western Australia, April 2010. Samples are coded by isobath.

Tropical continental shelves are characterised with turbid, low-density plumes associated with river discharge and these can form strong density fronts in coastal waters. These are known to influence the distribution and ecology of planktonic organisms (Grimes and Finucane 1991, Thorrold & McKinnon 1995, Grimes & Kingsford 1996). Although north-western Australia experiences significant rainfall (>1000 mm) during the summer monsoon, during 2010, there was atypical lower rainfall (BoM 2010) and, consequently, there was no evidence of turbidity fronts.

Continental shelf waters of the region are understood to experience a high degree of current variability in response to semi-diurnal tides and offshore forcing by regional currents at the shelf break (Holloway & Nye 1985, Holloway 1995). The horizontal velocity field indicated that alongshore advection, which attained velocities of up to 0.5 m s^{-1} , was generally greater than advection in the cross-shelf direction, particularly over the shelf. This is consistent with an earlier study of Holloway (1983) which showed that tidal velocities shift from cross-shelf at the shelf break and become predominantly along-shelf nearer the coast.

As illustrated by a station located in coastal waters, there was a breakdown of stratification corresponding with the high tide (vertical mixing) although the water column rapidly returned to stratified conditions on the

ebbing tide. Although strong temperature stratification of shelf waters persists over summer and autumn on the NWS (Van Gastel *et al.* 2009), vertical mixing is expected to periodically re-distribute planktonic biota and other properties of the water column.

Spatially, there was significant cross-shelf structuring of zooplankton bio-volume in relation to isobath. The biomass of zooplankton over tropical continental shelves is generally greatest in coastal waters (*e.g.* Nair *et al.* 1981, Wilson *et al.* 2003a, Munk *et al.* 2004) and associated with higher phytoplankton biomass (Wilson *et al.* 2003a, Lamb & Peterson 2005, Stenseth *et al.* 2006). The pattern of higher zooplankton bio-volume, including higher concentrations of larval euphausiids, in coastal waters off the Kimberley corresponded with the high chlorophyll *a* concentration (Thompson & Bonham this issue). Offshore, the correlation between phytoplankton and zooplankton biomass is known to be generally weaker due to the influence of physical processes which introduce strong variability to the distribution of planktonic biomass (Gibbons & Hutchings 1996).

Besides the common macro-zooplankton taxa such as copepods, euphausiids and chaetognaths, the diversity of zooplankton of the Kimberley during this study was enhanced by the occurrence of the pelagic larval stages of a number of benthic invertebrates. Off the southern NWS, Wilson *et al.* (2003a) described similar zooplankton

assemblages although the greater abundance of amphipods and cumaceans they reported may be related to their use of light traps for sampling. Although benthic marine invertebrates have widely contrasting reproductive strategies, the occurrence of their larvae indicates that spawning of some taxa occurs in the austral autumn. This is an important consideration when assessing the potential impacts of anthropogenic disturbance to the pelagic ocean in the Kimberley region.

The concentration of larval-stage euphausiids infers recent production and, as the larval duration is only a few days in warm water (Iguchi & Ikeda 1994), could support higher trophic levels, particularly plankton-feeding megafauna. In terms of species composition there was a clear cross-shelf pattern; coastal and inner shelf waters (50 m and 100 m isobaths, respectively) were dominated by *P. latifrons* and krill assemblages were much less speciose compared to those of outer shelf and oceanic waters that were dominated by larvae of the genus *Stylocheiron*. A similar study off the southern NWS also described the dominance of *P. latifrons* on the shelf (Wilson *et al.* 2003b). In general though, this study has only reported broad taxonomic groups for macro-zooplankton assemblages and it is possible that further spatial and temporal trends will be elucidated from a detailed analysis of their taxonomic composition and abundance.

Overall, the larval fish composition described for shelf and offshore waters off the Kimberley coast was consistent with that described by Young *et al.* (1996) for the southern NWS, and other tropical waters such as the Great Barrier Reef (Leis 1993) and the Andaman Sea (Munk *et al.* 2004). Depth-integrated larval fish assemblages displayed significant cross-shelf structuring in relation to isobath and, as with other studies (*e.g.* Harris *et al.* 2001, Gray & Miskiewicz 2000, Muhling *et al.* 2008), the coastal assemblage was the most distinct and had a higher diversity of neritic taxa. Notably, the occurrence of larvae of commercially valuable teleost fishes, such as the Lutjanidae, Serranidae and Scombridae, throughout the study region in autumn is an important consideration for environmental and fisheries management. Similarly, the prevalence of larvae of meso-pelagic oceanic Myctophidae warrants investigation of their biogeography and trophic significance in the eastern Indian Ocean (*e.g.* Kawamura 1994).

In general, the cross-shelf larval distributions of larvae of neritic and oceanic meso-pelagic fish taxa, is indicative of their dispersal by advective processes. However, we note that, in this study, the offshore occurrence of larvae of reef-dwelling fishes may have been sourced from the nearby Scott and Seringapatam Reefs which are located at the shelf break. Further, the less diverse larval fish assemblages of the Lacepede Islands and King Sound were distinct from the 50 m isobath assemblage suggesting less exchange between these unique locations and shelf waters. The restricted distribution of larval engraulids in coastal waters during this study is also suggestive of limited cross-shelf exchange as these larvae preferentially distribute themselves in near-surface waters making them susceptible to offshore wind-driven Ekman transport (Muhling & Beckley 2007). However, light winds prevailed for the duration of the Kimberley

voyage which did not favour this type of advective transport.

In the absence of frontal structures the observed cross-shelf distributions of macro-zooplankton and larval fishes could be related to other physical and / or biological processes (*e.g.* spawning areas) operating at a range of spatial and temporal scales which were not resolved in this study. For instance, the depth-integrated bongo tows (to 150 m depth) sampled both the shallow and deeper water masses occurring in the study region. They are also insensitive to small-scale vertical patchiness such as the association of zooplankton with the deep chlorophyll maximum (Cullen 1982). Depth-stratified sampling will be required to resolve such effects and may also elucidate diel influences which accounted for a small amount of the variability in the data. It is also probable that differences exist over the tidal cycle (*i.e.* between high and low tides) which analysis of additional data from the 24 hour sampling station should resolve.

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Appendix 1

One-way ANOSIM and SIMPER analyses between larval fish assemblages classified according to the factor of isobath. The species listed are those which contributed highest and most consistently to the differences between assemblages. The letter given in superscript (x for columns, y for rows) refers to the assemblage in which the given family was more abundant. Avg. Dissim. = average dissimilarity between stations.

	King Sound	Lacepede Is.	50 m	100 m	200 m	500 m	1000 m	2000 m
King Sound	Avg. Dissim. 72% Gobiidae							
Lacepede Is.	R = 0.7, p = 0.002 Engraulidae ^y Gobiidae ^y	Avg. Dissim. 40% Gobiidae Engraulidae Apogonidae						
50 m	R = 0.9, p = 0.002 Bregmacerotidae ^y Gobiidae ^y Sparidae ^y	R = 0.4, p = 0.002 Engraulidae ^y Bregmacerotidae ^y Gobiidae ^x	Avg. Dissim. 54% Engraulidae Bregmacerotidae Gobiidae Nemipteridae Apogonidae					
100 m	R = 0.9, p = 0.001 Myctophidae ^y Bregmacerotidae ^y Gobiidae ^x Sparidae ^x	R = 1.0, p = 0.001 Engraulidae ^x Gobiidae ^x Myctophidae ^y Bregmacerotidae ^y	R = 0.8, p = 0.001 Bregmacerotidae ^x Engraulidae ^x Gobiidae ^x	Avg. Dissim. 55% Bregmacerotidae Myctophidae				
200 m	R = 0.9, p = 0.001 Myctophidae ^y Gobiidae ^x Bregmacerotidae ^y Sparidae ^x	R = 1.0, p = 0.001 Engraulidae ^x Gobiidae ^x Myctophidae ^y	R = 0.8, p = 0.001 Bregmacerotidae ^x Engraulidae ^x Gobiidae ^x		Avg. Dissim. 64% Myctophidae Bregmacerotidae Champsodontidae Paralepididae			
500 m	R = 1.0, p = 0.001 Myctophidae ^y Gobiidae ^x Sillaginidae ^x Sparidae ^x	R = 1.0, p = 0.001 Engraulidae ^x Gobiidae ^x Myctophidae ^y	R = 1.0, p = 0.001 Bregmacerotidae ^x Engraulidae ^x Gobiidae ^x	R = 0.5, p = 0.001 Bregmacerotidae ^x Myctophidae ^y Champsodontidae ^x Gobiidae ^x		Avg. Dissim. 55% Myctophidae Bregmacerotidae		
1000 m	R = 1.0, p = 0.001 Myctophidae ^y Gobiidae ^x Sillaginidae ^x Sparidae ^x Apogonidae ^x	R = 1.0, p = 0.001 Engraulidae ^x Gobiidae ^x Myctophidae ^y	R = 0.1, p = 0.001 Bregmacerotidae ^x Engraulidae ^x Gobiidae ^x Myctophidae ^x Nemipteridae ^x	R = 0.5, p = 0.001 Bregmacerotidae ^x Myctophidae ^x Champsodontidae ^x Gobiidae ^x	R = 0.2, p = 0.001 Myctophidae ^x Bregmacerotidae ^x Champsodontidae ^x		Avg. Dissim. 60% Myctophidae Gonostomatidae	
2000 m	R = 0.1, p = 0.001 Myctophidae ^y Gobiidae ^x Sparidae ^x	R = 1.0, p = 0.001 Engraulidae ^x Gobiidae ^x Myctophidae ^y Nemipteridae ^x	R = 1.0, p = 0.001 Bregmacerotidae ^x Engraulidae ^x Gobiidae ^x Myctophidae ^x Nemipteridae ^x	R = 0.8, p = 0.001 Bregmacerotidae ^x Engraulidae ^x Gobiidae ^x	R = 0.3, p = 0.003 Myctophidae ^x Bregmacerotidae ^x	R = 0.2, p = 0.01 Myctophidae ^x Gonostomatidae ^y		Avg. Dissim. 57% Myctophidae Phosythyidae Gonostomatidae

The coastal habitats and vegetation of the Kimberley region

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Abstract

Incorporating the areas of the rocky Kimberley Coast, flanked by the deltaic gulfs of Cambridge Gulf and King Sound, as well as the Dampier Peninsula, the Kimberley region host a complicated coastal zone with a plethora of coastal habitats. The smallest scale of habitat includes rocky cliff, scree slopes, gravelly/bouldery shore, sandy beaches, spits, dunes, tidal mud flats, alluvial fans, and the contact between some of these habitats and freshwater. The main vegetation units include mangroves, shrubby chenopods (which include succulent halophytic shrubs), saline marsh, sedgeland, rushlands, dune scrub, dune grasslands, and teatree thickets. The spatially and temporally variable landscape, sediments/soils, and hydrochemistry expressed at the coast mean that the coastal vegetation habitats are the most complex habitats in the Kimberley region. This review found that to date these have not been fully explored or described botanically.

Keywords: Kimberley Coast, coast, coastal habitats, mangrove, saltmarsh, mangal, chenopod

Introduction

Perhaps the first general survey of coastal ecosystems in Western Australia was Sauer (1965), which dealt, *inter alia*, with the Kimberley coast. While there have been a limited number of works published focusing specifically on the flora and vegetation of the Kimberley region most of these have focused on specific habitats and formations such as the Kimberley Rain Forests (McKenzie *et al.* 1991), or on regions such as the Dampier Peninsula (Kenneally *et al.* 1996), Drysdale Nature Reserve (Kabay & Burbidge 1977), the Prince Regent River Nature Reserve (Miles & Burbidge 1975), Bougainville Peninsula, Osborn and Institut Islands (Beard *et al.* 1984), and Mitchell Plateau/Admiralty Gulf (Wells 2006). Flora and vegetation have also been noted in the studies of landforms of the Kimberley region undertaken by the Agricultural Department and the CSIRO (*e.g.*, Speck 1960; Speck *et al.* 1964), and more regional surveys and characterisations such as that undertaken by Beard (1979). Furthermore key works have been published that provide diagnostic and ecological data on the flora (Wheeler *et al.* 1992), or checklists of presence of plant species within the Kimberleys (Kenneally 1989). However, to date, apart from studies of mangroves and saline marsh (Wells 1979 1981; Semeniuk 1980, 1983, 1985; Bridgewater 1982, 1985, 1989; Bridgewater & Cresswell 1993, 1999, 2003, Cresswell & Bridgewater 1998), there has been little focus on flora and vegetation specific to the coastal zone. The coastal zone is the most classic ecotone, where a wide range of environmental factors combine to provide templates and stimuli for the development of complex mosaics of plant communities.

While vegetation (and flora) of the 'inland' Kimberley region can be related clearly to underlying rock

formations, soils, water availability, and climate; in the coastal zone vegetation distribution (and its component flora) responds to a wider variety of environmental factors including physiography, groundwater characteristics and climate, together with the effect of sea spray. Variation in the climate, landforms, soils, and habitats of the 'inland' Kimberley Plateau, for instance, does result in complex vegetation, including some very specific micro-climate controlled habitats, or those where there is freshwater seepage on basalt slopes and vine thickets are developed; or the narrow deeply incised valley tracts with local freshwater springs where *Pandanus* dominated wetlands are found.

In general, the 'inland' Kimberley Plateau vegetation is relatively consistent across its 16,000 square kilometres of sandstone and basalt plateaux (Griffin & Grey 1990a, 1990b) compared to the coastal zone. Similarly there is a relative consistency across the Dampier Peninsula of a relatively uniform geology (Gozzard 1988). The greatest environmental determinant of vegetation distribution across these inland terrestrial environments across the entire region is rainfall and water availability. The Kimberley coastal zone, however, is more variable spatially and temporally, and this variability is expressed through complex vegetation patterning. It is spatially variable because, as an ecotone between terrestrial and marine environments, it is subject to marine processes that are variably developed along the coast, (*i.e.*, different wave energy, tides, orientation of coast, sediment supply, sediment type, and coastal landforms) resulting in a wide range of coastal physiographic templates: sea cliffs, beaches, dunes, tidal flats, muddy embayments, amongst many others. The coastal zone exhibits greater temporal variability in habitat development because it is subject to marine processes that can create, modify and destroy habitats (*e.g.*, the development of barrier sand bars, dune formation, and collapse of sea cliffs, amongst others). The study of the flora and vegetation of the Kimberley coastal

zone provides opportunity to identify ecological patterns and set a framework for understanding broad biogeography, which in turn informs conservation policy.

A number of authors refer to vegetation that inhabits coastal settings in the Kimberley region, but the descriptions have not been focused specifically on the coastal effects on determining vegetation and its composition. For instance, Hnatiuk & Kenneally (1981) recognise 'Cliff Face Communities' as a distinct vegetation unit in the region, however they do not differentiate those which are coastal facing and subject to marine influences from those that are further inland. On the other hand, where there is recognition of coastal habitat, it is too broad, and not related to a specific habitats; e.g., Hnatiuk & Kenneally (1981) recognise a 'Strandline Communities' containing a limited set of species including small trees, climbers and graminoids, but it is difficult to ascertain what exactly constitutes a strandline, and whether it incorporates habitats such as beach crest, salt flat edge, bouldery shores, cliff shores, chenier margin, amongst others. Kenneally *et al.* (1991) in a study of floristics of rainforests in the Kimberley region record some occurrences of vegetation types at the coast, however, given the stratigraphic and hydrological underpinning of the occurrence of the rainforests, their analysis did not differentiate whether these coastal occurrences are just stratigraphic and hydrologic manifestations of the habitat at the coast or whether the rainforest is structurally or floristically distinct from inland rainforest.

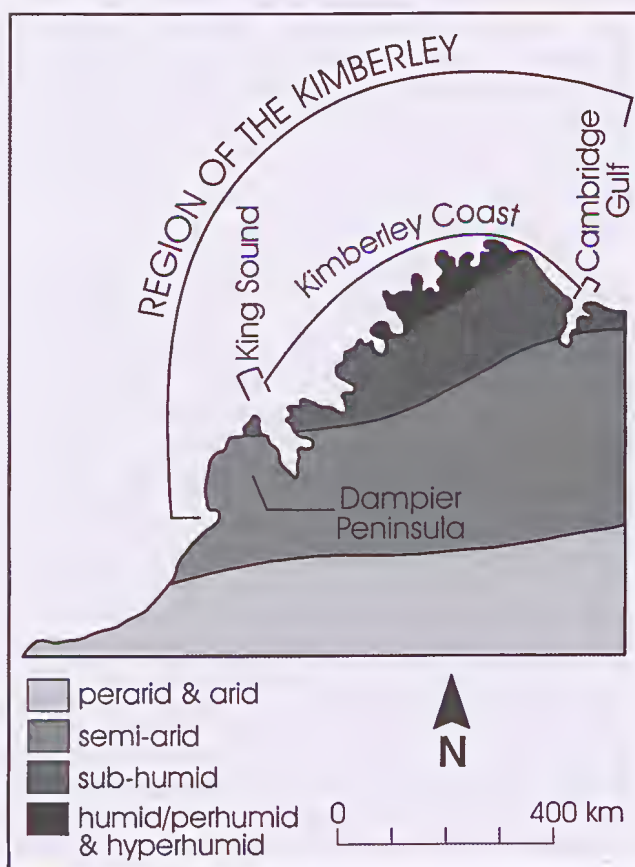


Figure 1. Location map of the Kimberley region comprising the Kimberley Coast, King Sound, Cambridge Gulf, and the Dampier Peninsula, and their climate setting.

McKenzie *et al.* (1991) undertook a quantitative analysis of the floristic and faunistic composition of a set of representative samples of Kimberley rainforest patches. This revealed only one type that was restricted to near-coastal locations (within which only one group had not been extensively damaged by cattle, consisting of a low scrubby patch on an isolated Quarternary coastal sand dune towards the seaward edge of an extensive tidal mudflat in the far northeastern Kimberley). However, because of a correlation between annual rainfall and proximity to the coast in the North Kimberley, the analysis also showed that scree slope and riparian patches near to the coast were larger and had a wider array of species than their inland counterparts (McKenzie *et al.* 1991, McKenzie *pers. com.* 2011).

Kenneally *et al.* (1996) in a study of the Dampier Peninsula characterise some of its coastal vegetation into broad habitats such as seepage zones, coastal dunes, and limestone outcrops, and lists some of the vegetation in structural terms such as saline grasslands, samphire (shrubby chenopods in our terms) flats and mangroves, as well as some lists of key species that characterise the habitats or vegetation formations.

As part of this Symposium on the Kimberley marine and coastal environments we have endeavoured to review the information on the flora and vegetation of the Kimberley region (Fig. 1), through the lens of our own data and experiences, and present a broad description of the coastal habitats and vegetation of the Kimberley region.

The objectives of this paper are to describe the abiotic habitats (the geological, landscape and climate-determined templates of vegetation), set these various habitats within the major geological/physiographic subdivisions of the Kimberley region, describe the broad phytogeography and, as the limits of literature and our experience permit, describe some of the main elements of the Kimberley vegetation as it responds to geology, landscape, and climate in the coastal zone.

Terms and methods

'Coastal' means that environment that is the land-sea interface, and is inundated by tides or is influenced by maritime processes such as salt spray, storm surge *etc.* We include in coast the strip of land between terrestrial and marine environments, between low tide and high tide, as well as the area adjoining the marine environment that is still influenced by maritime processes, e.g., salt spray, sea-derived winds, and cyclone-elevated sea levels, and those habitats formed in the very recent past by coastal processes but now are above prevailing high tide. The definition of 'coastal zone' is relatively straightforward where there are sea cliffs, sand dunes, and a distinct high-tidal mark, but is more difficult where broad alluvial plains grade into the coastal zone.

Defining 'coastal vegetation' is more difficult. Vegetation that is inundated by tides, or that which occupies saline or hypersaline conditions, or preferentially inhabits the zone of sea spray and salt-bearing winds, can be assigned to the category of 'coastal'. However vegetation or species inhabiting the

strandline, or a sea-facing cliff, does not mean that vegetation or a species is purely 'coastal' if they also occur inland in the same composition. Rainforests illustrate this principle: the composition and structure of rainforest inhabiting soil-moist slopes of basalt that adjoin cliffs of fractured sandstone inland may be the same as that along ocean-facing cliffs. Only rainforest that compositionally or structurally reflects maritime condition is 'coastal'. Figure 2 presents several examples of vegetation growing at the coast which is not by our definition 'coastal'.

The study of the habitats and vegetation of this coastal region is based on literature review and our own extensive field work and sampling sites as noted in Bridgewater (1982, 1985, 1989), Bridgewater & Cresswell (1993, 1998, 1999, 2003), Cresswell & Semeniuk (2011), Semeniuk (1980, 1983, 1985 1986, 2008, 2011).

The study area – what do we mean by the 'Kimberleys'?

The Kimberley region has various definitions. Administratively, and in more general usage, the Kimberley region extends from the Northern Territory border (the eastern Kimberley), across the plateaux (the Kimberley Plateau) between Cambridge Gulf, Fitzroy River and King Sound, to the Dampier Peninsula as far south as Eighty Mile Beach. Reflecting its climate setting the 'Kimberleys' are a much smaller area, encompassing the eastern Kimberley, the Kimberley Plateau(x), the Fitzroy River valley tract, King Sound, and the Dampier Peninsula. Geologically and physiographically it is even smaller, and the Kimberley geological region consists of the Kimberley Plateau and the bordering McLarty Ranges (the area of the Dampier Peninsula and King Sound belong to the Canning Basin, whereas Cambridge Gulf is part of the Bonaparte Gulf Basin and the Halls Creek Province).

Given the major influence of climate as a driver of the distribution of biota, the Kimberley region biogeographically commonly is delineated on its broader definition (and not solely based on geological precepts). Using this broader definition of the Kimberley region adopted for this Symposium, it is useful to delineate the four geological and physiographic units and their coastal expressions, namely, from north to south:

1. Cambridge Gulf, comprising coastal units of alluvial plains, rocky ranges, and broad tidal flats;
2. Kimberley Coast (*sensu* Semeniuk 1993), comprising coastal units mainly of rocky shores, ria embayments, sandy coves;
3. King Sound Gulf, comprising coastal units of alluvial plains, red sand dunes, and broad tidal flats;
4. Dampier Peninsula, comprising coastal units on its western side of sea cliffs, tidal embayments, sandy coves and sandy barriers.

These units will form the natural large scale physiographic units within which we will place the various smaller scale coastal habitat templates. The coastal distribution of these units is shown in Figure 1.



Figure 2. Examples of terrestrial vegetation at the coast. A. Steep vegetation-free cliff truncating the terrestrial vegetation at the top; slope is vegetated by scree vegetation; thin bleached zone is the level of the highest tides; boulder tidal zone is mangrove free. B. Terrestrial vegetation (plateau top and valley type) truncated at cliff, a crumbling cliff; bleached zone is the level of the highest tides. C. Terrestrial vegetation truncated at cliff; scree slope with scree vegetation; *Triodia* almost to the foot of the scree; bleached zone is the level of the highest tides. D. *Triodia* on cliff face; brown zone of rock face is above the level of the highest tides and all vegetation is terrestrial; top of bleached zone is the level of the highest tides.

Table 1

Main habitats of the coastal zone (scale of reference modified from Semeniuk 1986)

Major geological/physiographic unit (regional scale)	Large scale landforms	Medium to small scale landforms (= physiographic habitats), in general order of abundance
Cambridge Gulf	alluvial plains, rocky ranges, broad tidal flats	tidal mud flats, rocky cliffs, sandy beaches, sandy cheniers, coastal scree slopes
Kimberley Coast	rocky shores, rias, embayments, sandy coves, sandy barriers	rocky cliffs, terraced cliffs, coastal scree slopes, gravelly/bouldery shores, tidal mud flats, sandy beaches, sandy cheniers, sandy spits, dunes, alluvial fans, alluvial fan to tidal flat freshwater interface, rocky slope and salt flat freshwater interface, dune to tidal flat freshwater interface, beach rock ramps
King Sound	alluvial plains, red sand dunes, and broad tidal flats	tidal mud flats, sandy beaches, sandy cheniers, sand cliffs, red sand dune freshwater seepage zones
Dampier Peninsula	sea cliffs, tidal embayments, sandy coves, sandy barriers	rocky cliffs, sandy beaches, beach rock ramps, alluvial fans, alluvial fan to tidal flat freshwater interface; dune freshwater seepage zones; freshwater ponds

Table 2

Description of habitats and occurrence of vegetation

Habitat unit	Description of habitat
rocky cliff	coastal rock face that may be vertical or steeply inclined, and with terraces; if terraced, smaller scale aprons of scree separate the vertical faces; scree slopes are gravel, sandy gravel, and muddy gravel; rock may be sandstone or basalt
terraced cliff	coastal rock face (usually a sandstone/basalt contact) that is prominently terraced, with or without scree separating the vertical faces; faces are vertical or steeply inclined; smaller scale aprons of scree separate the low vertical faces; scree slopes are gravel, sandy gravel, and muddy gravel
coastal scree slope	scree slopes of gravel, sandy gravel, and muddy gravel
gravelly/bouldery shore	steep to moderately sloping rocky tidal surface with veneer of gravel and boulders
sandy beach, sandy chenier, sandy spit dune	moderately sloping to hummocky sandy tidal surface, rising upslope to supratidal and passing into dunes hummocky sandy terrain, above tidal levels
coastal dune barring drainage or freshwater seepage	depression or swale between coastal dunes and the hinterland where freshwater drainage or freshwater seepage from the land is barricaded to form a shore-parallel wetland; this is the area where coastal vine thickets may be developed
sand cliff	cliff cut into sand dune, particularly Pleistocene red sand dunes that are more cohesive to cliff erosion; steep sandy slope or face
limestone cliff	cliff cut into Holocene or Pleistocene limestone dune
tidal mud flat	low gradient tidal muddy surfaces; high tidal zones are commonly hypersaline and thus salt flats
alluvial fan	low gradient gravelly to sandy to muddy surfaces at EHWS
alluvial fan to tidal flat freshwater interface	sharp interface between alluvial fan and salt flat where there is freshwater seepage from the alluvial fan diluting the salt flat hypersalinity
rocky shore and salt flat freshwater interface	sharp interface between rocky slope and salt flat where there is freshwater seepage from the rocky uplands diluting the salt flat hypersalinity
red sand dune to tidal flat freshwater interface	low-gradient interface between red sand desert linear dunes and salt flat where there is freshwater seepage from the dune sand diluting the salt flat hypersalinity
dune to tidal flat freshwater interface	sharp interface between coastal dunes and salt flat where there is freshwater seepage from the dune sand diluting the salt flat hypersalinity
beach rock ramp	moderately sloping rock pavement tidal surface, rising upslope to supratidal sand and locally passing into dunes; mangroves may inhabit the tidal slope seaward of the ramp
freshwater pond	rounded to oval freshwater ponds along the high tidal zone; excavated by solution of carbonate muds

Superimposed on the geological grain of the region and the large scale physiographic units is climate (Fig. 1). In this part of Western Australia, the most humid region is centred on the near-coastal and coastal areas of the north-western Kimberley region in the Mitchell Plateau area. Gradational from this region in northerly and southerly directions, the climate is subhumid and semiarid, respectively. Another factor in the development of habitats and occurrence of biota along the coastal zone is drainage, which is the delivery to the coast of water via local freshwater seepage zones, and rivers, creeks and rivulets.

The major coastal habitats

Within the four major natural geological and physiographic units listed above, there are a large range of smaller scale coastal habitats, delineated by their abiotic characteristics of landforms, sediments/ soils, water features, salinity, and exposure to salt spray. Table 1 provides an hierarchical framework classifying the main habitats of the coastal zone. At the largest scale the major geological/ physiographic units relate to an expression of the geology and physiography of the landscape at the regional scale, generally measured in hundreds of kilometres. Beneath that large scale landforms are an expression of physiographic form generally at the 50–10 km frame. The finest scale landforms (medium to small scale) relate to the expression of landforms as physiographic habitats generally in frames of 1 km down to 100–10 metres.

The geological/physiographic unit containing the greatest number of smaller scale coastal habitats is the Kimberley Coast. A description of smaller scale coastal habitats is presented in Table 2. A selection of key coastal habitats is illustrated in Figure 3. The description of the smaller scale habitats which determine vegetation are not described to the next level of detail (*i.e.* the gradients internal to the habitat in terms of salinity, inundation frequency, and distance from shore and hence sea spray and salt-laden winds).

Coastal Vegetation

Broadly, coastal vegetation in the region can be divided into mangroves, shrubby chenopods (which include succulent halophytic shrubs), saline marshes, sedgeland and rushlands, dune scrub, dune grasslands, and Teatree thickets. Vegetation of coastal habitats is divided into two zones: that located in the tidal zone and that which is supratidal, *i.e.*, straddling the high tide mark, and that above the high tide mark but subject to salt spray, coastal wind, and storm surges. Some key indicator species of the vegetation in these habitats are provided in Table 3. We have emphasised the mangrove and saline marsh species because these systems have had the most attention. Future work is clearly needed on cliff vegetation, and the ecotones between coastal and terrestrial vegetation. A selection of coastal vegetation from the Kimberleys is illustrated in Figure 4.

Previous descriptions of the vegetation of the tidal flats, alluvial fans, gravelly and bouldery shores.

The combination of abiotic habitats described above form the basis for some of the most characteristic and extensive coastal-specific vegetation in the Kimberley region, namely; mangal forest, mangrove or chenopod shrublands and associated wet or often-dry saline marshes.

Bridgewater & Cresswell (1999), describe the region as the Dry tropical *Camptostemon-Avicennia-Batis* Division in an Australia-wide analysis of mangrove and saltmarsh. They recognise the Kimberley as an important region in the Australian mangrove distribution. While not as species-rich or lush as the north eastern or northern Australian mangrove systems, the Kimberleys have a high level of vegetation heterogeneity in response to the high diversity of coastal abiotic habitats described above. Similarly, Bridgewater (1985, 1989) identifies a number of mangrove and saline marsh communities in the region. At the highest level the following phytosociological classes are described in Bridgewater (1989) *Avicennietea*, *Avicennio-Cerriopetea* from eulittoral to supralittoral, and where there is saline marsh this is represented by the *Halosarcio-Avicennietea*.

There are a large number of communities possible, and in any particular location, there is a wide range of width and extent of vegetation to develop. Extent of freshwater seepage from land, and the nature of substrate are the other two key variables influencing vegetation expression. From eulittoral to supralittoral the key defining species of (often monospecific) vegetation communities are *Sonneratia alba* (especially in the north of the region), *Avicennia marina*, *Rhizophora stylosa*, *Aegialitis annulata* (most frequently lining tidal creeks), *Camptostemon schultzei* - *Bruguiera exaristata*, *Xylocarpus moluccensis* - *Cerriops tagal* - *Lumnitzera racemosa*, *Excoecaria agallocha* - *Osbornia octodonta* (especially in more sandy/ rocky areas). In the higher eulittoral to supralittoral range the following are typical *Cerriops tagal*, *Excoecaria agallocha*, and in hypersaline dry flats stunted *A. marina* with shrubby chenopods.

At the highest supralittoral levels, where freshwater seepage is rare or absent the following are typical *Tecticornia halocnemoides* ssp. *tenuis*, *Tecticornia indica* subsp. *leiostachya*, *Suaeda arbusculoides* and *Batis argillicola*. Depending on the substrate, a flora dominated by graminoids may also develop (*Sporobolus virginicus*, *Xerochloa imberbis*, and various cyperoid species).

In areas where there are extensive open mud flats the *Tecticornietea* (Bridgewater, 1989) occurs. This is a simple, annual vascular plant community dominated by *Tecticornia verrucosa*. The mud surface is however covered also by extensive algal flora, including many diatom species.

The determinants for the complex range of vegetation types described above are substrate, distance and slope from eulittoral to supralittoral, and the influence of freshwater flow or seepage. The relatively depauperate flora combines in a number of distinct and identifiable communities, determined by the expression of these physical variables in the many different habitats that are

Table 3

Occurrence of vegetation with respect to coastal habitats

Habitat unit	Some key indicator species
rocky cliff	<i>Sesuvium portulacastrum</i> ; <i>Ficus</i> spp. ¹ , <i>Scaevola taccada</i> , <i>Thespesia populneoides</i>
terraced cliff	<i>Sesuvium portulacastrum</i> ; <i>Ficus</i> spp. ¹ , <i>Scaevola taccada</i> , <i>Thespesia populneoides</i>
coastal scree slope	<i>Sesuvium portulacastrum</i> ; <i>Ficus</i> spp. ¹
gravelly/bouldery shore	<i>Avicennia marina</i> ² , <i>Ceriops tagal</i> , <i>Excoecaria agallocha</i> , <i>Lumnitzera racemosa</i> , <i>Rhizophora stylosa</i> , and <i>Sonneratia alba</i> ; supralittoral may have areas of saline slopes with <i>Sporobolus virginicus</i> , <i>Tecticornia halocnemoides</i> subsp. <i>tenuis</i> , <i>Frankenia ambita</i> , <i>Suaeda arbusculoides</i> , <i>Sesuvium portulacastrum</i>
sandy beach, sandy chenier, sandy spit	The vegetation is patchy with tree, shrub or low shrub/graminoid dominated patches, with a range of species possible: <i>Avicennia marina</i> , <i>Rhizophora stylosa</i> , <i>Ceriops tagal</i> , <i>Osbornia octodonta</i> , <i>Bruguiera exaristata</i> , and <i>Aegialitis annulata</i> ; <i>Spinifex longifolius</i> , <i>Fimbristylis cymosa</i> , <i>Fimbristylis sericea</i> , <i>Cyperus bulbosus</i> , <i>Ipomoea pes-caprae</i> subsp. <i>brasiliensis</i> , <i>Suaeda arbusculoides</i> , <i>Euphorbia myrtilloides</i> , <i>Euphorbia plumerioides</i> , <i>Acacia bivenosa</i> , <i>Lysiphyllum cunninghamii</i> , <i>Canavalia rosea</i> , <i>Scaevola taccada</i> , and <i>Thespesia populneoides</i>
dune	<i>Spinifex longifolius</i> , <i>Fimbristylis cymosa</i> , <i>Fimbristylis sericea</i> , <i>Cyperus bulbosus</i> , <i>Ipomoea pes-caprae</i> subsp. <i>brasiliensis</i> , <i>Salsola kali</i> , <i>Euphorbia myrtilloides</i> , <i>Acacia bivenosa</i> , <i>Ficus opposita</i> , <i>Lysiphyllum cunninghamii</i> , <i>Canavalia rosea</i> , <i>Abutilon indicum</i> , <i>Clerodendrum tomentosum</i> , <i>Crotalaria cunninghamii</i> , <i>Hypoestes floribunda</i> , <i>Jasminum didymum</i> , <i>Mallotus nesophilus</i> , <i>Myoporum accuminatum</i> , <i>Ptilotus exaltatus</i> , <i>Santalum lanceolatum</i> , <i>Whiteochloa airoides</i> , <i>Pandanus spiralis</i>
coastal dune barring drainage or freshwater seepage	coastal vine thickets variable across the region but comprised of <i>Bridelia tomentosa</i> , <i>Celtis philippensis</i> , <i>Croton habrophyllus</i> , <i>Dioscorea bulbifera</i> , <i>Diospyros buukeyana</i> , <i>Diospyros ferrea</i> var. <i>humilis</i> , <i>Diospyros maritima</i> , <i>Exocarpos latifolius</i> , <i>Ficus virens</i> , <i>Glycosmis</i> spp., <i>Grewia breviflora</i> , <i>Grewia retusifolia</i> , <i>Melaleuca dealbata</i> , <i>Minusops elengi</i> , <i>Pavetta kimberleyana</i> , <i>Pittosporum moluccanum</i> , <i>Pouteria sericea</i> , <i>Prenna acuminata</i> , <i>Syzygium eucalyptioides</i> subsp. <i>bleeseri</i> , <i>Terminalia petiolaris</i> , <i>Terminalia ferdinandiana</i> and <i>Vitex glabrate</i> , with the vines <i>Abrus precatorius</i> , <i>Gynnanthera oblongata</i> , <i>Jacquemontia pauciculata</i> , <i>Passiflora foetida</i> , <i>Tinospora smilacina</i> and <i>Tylophora cinerascens</i>
sand cliff	<i>Cyperus bulbosus</i> , <i>Ipomoea pes-caprae</i> subsp. <i>brasiliensis</i> , <i>Suaeda arbusculoides</i> , <i>Salsola kali</i> , <i>Euphorbia myrtilloides</i> , <i>Euphorbia plumerioides</i> , <i>Scaevola taccada</i>
limestone cliff	<i>Ficus</i> spp. ¹ , <i>Scaevola taccada</i> , <i>Spinifex longifolius</i> , <i>Canavalia rosea</i> , <i>Ipomoea pes-caprae brasiliensis</i>
tidal mud flat	Between MSL and MHWS patchy communities dominated by a range of mangroves including <i>Avicennia marina</i> , <i>Rhizophora stylosa</i> , <i>Sonneratia alba</i> , <i>Bruguiera exaristata</i> , <i>Aegialitis annulata</i> , <i>Aegiceras corniculatum</i> , <i>Canptostemon schultzei</i> , <i>Bruguiera parviflora</i> , <i>Ceriops tagal</i> , <i>Excoecaria agallocha</i> , <i>Lumnitzera racemosa</i> , <i>Osbornia octodonta</i> , <i>Xylocarpus moluccensis</i> , <i>Xylocarpus granatum</i> , and at levels between MHWS and EHWS shrubby <i>Avicennia marina</i> , <i>Batis argillicola</i> , <i>Tecticornia halocnemoides</i> ssp. <i>tenuis</i> , <i>Neobassia astrocarpa</i> , <i>Suaeda arbusculoides</i> , <i>Sesuvium portulacastrum</i> , <i>Sporobolus virginicus</i> , <i>Xerochloa imberbis</i>
alluvial fan	<i>Avicennia marina</i> , <i>Bruguiera exaristata</i> , <i>Ceriops tagal</i> , <i>Excoecaria agallocha</i> , <i>Lumnitzera racemosa</i> , (<i>Rhizophora stylosa</i>), <i>Xylocarpus moluccensis</i> , <i>Xylocarpus granatum</i> ; the higher or supratidal range may be covered by saline or brackish marshes, dominated by sedges, grasses, and shrubby chenopods
alluvial fan to tidal flat freshwater interface	Sharp interface between alluvial fan and salt flat where there is inhabited by mangroves <i>Avicennia marina</i> , <i>Ceriops tagal</i> , <i>Excoecaria agallocha</i> , <i>Lumnitzera racemosa</i> , or by sedges, grasses, and shrubby chenopods
rocky shore and salt flat freshwater interface	<i>Avicennia marina</i> , <i>Ceriops tagal</i> , <i>Excoecaria agallocha</i> , <i>Lumnitzera racemosa</i> , may include also patches of low shrub dominated vegetation
red sand dune to tidal flat freshwater interface	Depending on salinity and location of the contact, <i>Melaleuca acacioides</i> , <i>Melaleuca cajuputi</i> and <i>Melaleuca uervosa</i> , with an understorey of Cyperaceae (including <i>Schoenoplectus litoralis</i>) and graminoids, and locally <i>Avicennia marina</i> , <i>Lumnitzera racemosa</i> , <i>Tecticornia halocnemoides</i> subsp. <i>tenuis</i> , <i>Frankenia ambita</i> , <i>Suaeda arbusculoides</i> , and <i>Batis argillicola</i>
coastal dune to tidal flat freshwater interface	Heterogeneous patches of vegetation types can be found in this highly diverse abiotic environment, which also exhibits strong temporal variation; typical species or species groups found include <i>Avicennia marina</i> , <i>Ceriops tagal</i> , <i>Excoecaria agallocha</i> , <i>Lumnitzera racemosa</i> , various sedges, grasses, and shrubby chenopods
beach rock ramp	<i>Avicennia marina</i> and <i>Ceriops tagal</i> ; mangroves are found on the tidal slope seaward of the ramp; dune vegetation (as above) on the supratidal zones
freshwater pond	Depending on the brackishness of the water <i>Avicennia marina</i> , <i>Excoecaria agallocha</i> , and <i>Lumnitzera racemosa</i> may inhabit the margins of these ponds, or with fresher states <i>Melaleuca dealbata</i> , <i>Melaleuca cajuputi</i> and/or <i>Pandanus</i> with Juncaceae and Cyperaceae forming an understorey

¹ It has not been possible to differentiate from the literature those *Ficus* species that occur in coastal settings as *Ficus* species are distributed on rocky screes, ridges and cliff substrate wherever it is available

² It is likely both subspecies *marina* and *eucalyptifolia* occur in the Kimberley. The precise ecological segregation of these subspecies, or more importantly undescribed genotypes, remains unclear, but is an area of important future research,

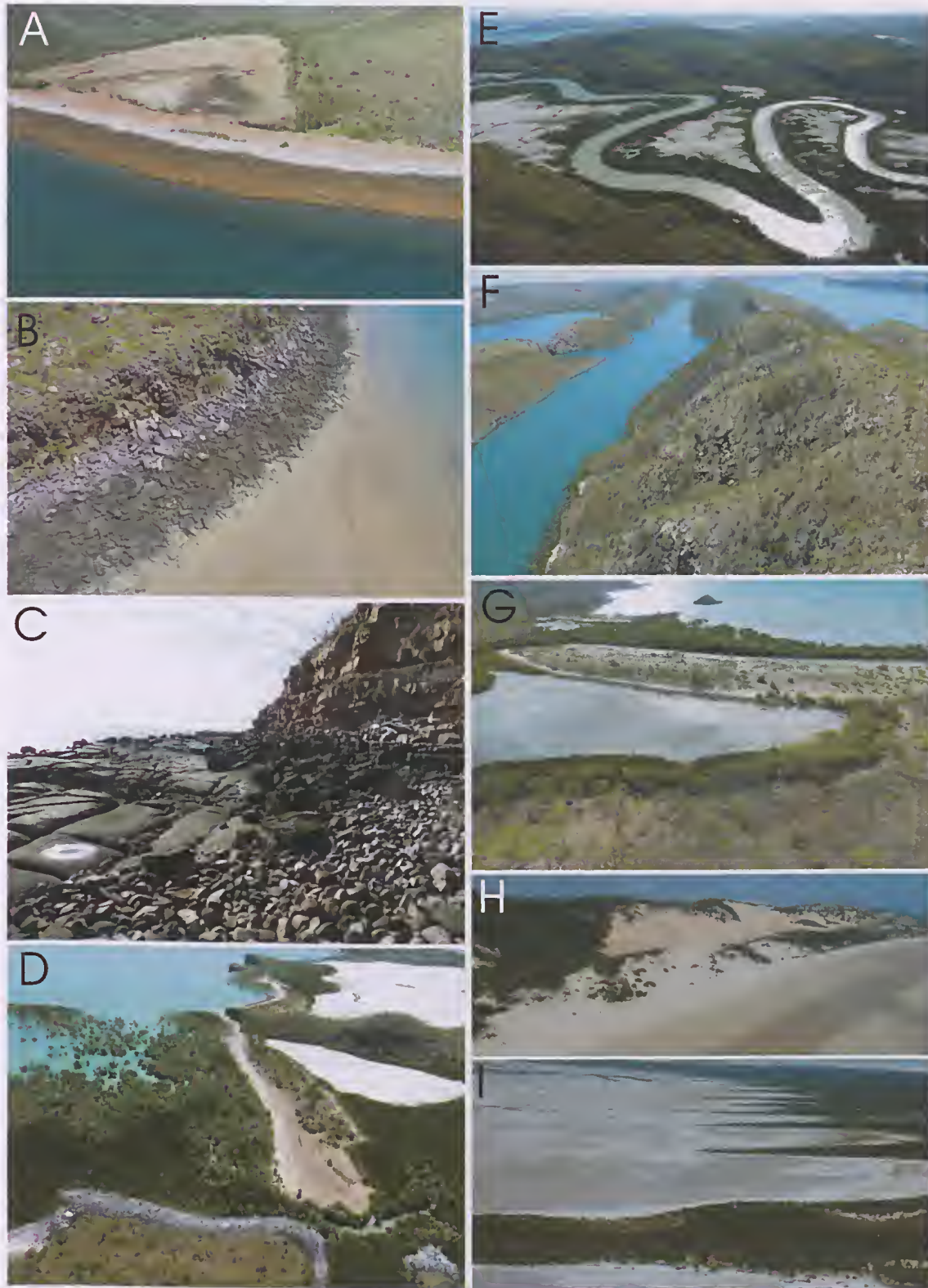


Figure 3. Examples of coastal zone habitats and coastal vegetation. A. Bar and lagoon with mud filled lagoon, hinterland fringed by Teatree (*Melaleuca* spp.), inside of bar with *Melaleuca* spp. and mangroves, crest of bar shrub-covered. B. Terrestrial vegetation truncated at cliff, some vegetation creeping down the cliff and high wave energy labile slope of boulder slabs is vegetation free; bleached zone is the level of the highest tides. C. Vegetation-free cliff with *Triodia* creeping down the top of the cliff and inhabiting ledges. D. Richly patterned habitats of gravel bars, sand bars, gravelly tidal flats, some cliffs; complex mangal vegetation as a result; crest of sand bar is *Pandanus*, *Melaleuca* spp. and grassy swards of *Sporobolus*. E. Tidal creeks and tidal flats in a valley tract bordered by vegetated terrestrial slopes, resulting in complex mangal and saline marsh vegetation. F. Vegetated slopes of the rocky ridges; bleached zone is the level of the highest tides; mangals in rocky shore tidal zone. G. Bar and lagoon with complex mangal on seaward side of bar, and fringing the hinterland of the lagoon and the inner side of the bar; crest of bar with *Triodia* and shrubs. H. Foredunes and large dunes to landward inhabited by various dune vegetation. I. Linear red sand dunes interfacing with and underlying the salt flat at the level of the highest tides; the vegetation is *Melaleuca* spp., and where freshwater discharges under the salt flat, *Avicennia marina*, *Melaleuca* spp. or samphires.



Figure 4. Examples of coastal zone habitats and coastal vegetation. A. In the foreground, shrubby chenopod (*Tecticornia halocnemoides* ssp. *tenuis*), with salt tolerant grasses *Sporobolus virginicus* and *Xerochloa imberberis*, and emergent *Excoecaria agallocha*; in the background low shrubs of *Ceriops tagal* and *Avicennia marina* (high tidal zone, western Dampier Peninsula). B. Complex mangal vegetation appearing as "zones" on a broad tidal flat. C. Complex mangal vegetation appearing as "zones" of mangrove inhabiting a tidal gravel flat and abutting a slope covered with terrestrial vegetation. D. E. Sand ridge above the level of the highest tides and complex mangal vegetation in swales between ridges; leeward of sand ridge fringed by mangal. F. Rocky shore with mangrove. G. Dune crest: *Pandanus* with graminoids. H. *Spinifex longifolia* and other species on a foredune. I. Creeper *Canavalia rosea* and shrub *Thespesia populneoides* on limestone slab rubble of cyclone deposit just above the level of the highest tides. J. Edge of a high-tidal alluvial fan; foreground of grasses with scattered shrubs of *Avicennia marina*, far-ground of complex mangal with *Avicennia marina*, *Ceriops tagal*, and *Bruguiera exaristata*.

expressed at the coast. While the system may appear floristically simple, the expression of the vegetation in these habitats is much more complicated than that presented by Hnatiuk & Kenneally (1981).

Discussion

The review above, the description of habitats, and analysis of vegetation with respect to habitat types, illustrate richness of flora and vegetation in the coastal Kimberley region.

Coastal habitats, as described in this paper, are variable in landscape, sediments and soils, and are subject to inundation and to waters of salinity ranging from freshwater, marine to hypersaline. Further, they are exposed to sea spray, to coastal winds, and to salt-laden winds. Additionally, they exhibit temporal variation. While inland habitats manifest long term (geological) stability, coastal habitats can be sedimentologically-built, removed, or substantially modified in the short term, and very short term due to wind, tides, waves, and storms. With coast dynamics and coastal processes, the salinity regimes maintaining coastal vegetation also can be markedly altered in the short term. The coastal zone is the zone of mixing between terrestrial freshwater, brackish water, sea water and evaporation-concentrated sea water, providing a wealth of interactions. Effectively, because of spatially and temporally variable landscape, sediments/soils, and hydrochemistry, the coastal vegetation habitats are the most complex habitats in the Kimberley region and, yet, least explored botanically.

Our use of habitat/floristic variation/vegetation expression forms a useful tool to describe the variation in coastal systems of the Kimberley, as well as providing a platform for monitoring and further research. In terms of conservation, the system we have exposed allows informed choices for coastal land and sea use to be made. The full implementation of our approach to documenting coastal vegetation provides an understanding of both temporal and spatial variation in vegetation, such that future conservation choices should not necessarily be restricted to areas that are apparently rare or restricted in a spatial sense; rather it allows for a more dynamic approach to conservation planning and especially management.

Current Conservation status of the coastal vegetation in the Kimberleys

The existing conservation reserves containing coastal vegetation in the Kimberley region are the Mitchell River National Park and the Prince Regent Nature Reserve. Much of the remaining coastline north of King Sound is included within extensive Aboriginal lands which are managed by the Traditional Owners to ensure ecological values are maintained.

In 2009 the Western Australian government announced the Camden Sound Marine Park for marine conservation containing the St George Basin estuary system to the high water mark including extensive mangrove forests adjacent to the Prince Regent Nature Reserve. The St George Basin estuarine environment is

heavily influenced by freshwater flow from the Prince Regent River which runs almost entirely straight along a fault or fracture through the King Leopold Sandstone. The final decision on the proposed marine park had not been made as at the end of February 2011.

In 2008 the Australian and Western Australian governments agreed to undertake an assessment of the west Kimberley including coast areas to identify its National Heritage (and potential international heritage) values. Subsequently the Australian Heritage Council (AHC) undertook an assessment of the west Kimberley to determine those areas with National Heritage values, for possible inclusion in the National Heritage listing under the Environment Protection and Biodiversity Conservation Act 1999, which would provide recognition and protection of any outstanding heritage values in the west Kimberley. The AHC's preliminary assessment noted that the spectacular west Kimberley coast (from King Sound near Derby to Bonaparte Gulf near Wyndham) is the longest stretch of predominantly rocky coast in Australia (Brocx & Semeniuk 2011) being a drowned river landscape including headlands and archipelagos, deep bays, impressive tidal effects and waterfalls, undisturbed by major coastal infrastructure. Moreover it found that 'contemporary refugia, such as the Kimberley, can be regarded as 'natural laboratories' for the study of ecological and evolutionary processes. The coast and islands, vine thickets, mangroves, karst areas and northern and western rivers are particularly important for protecting species and ecosystems which are rare, unknown or threatened elsewhere'.

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Freshwater seepage along the coast of the western Dampier Peninsula, Kimberley region, Western Australia

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Abstract

Controlled by the stratigraphic relationships along the shore of the western Dampier Peninsula, there are several mechanisms that deliver freshwater of the hinterland to the shore zone. These include seepage along the edge of the red sand dunes, rivulets discharging into tidal embayments, impounding of rivulets and streams by dunes, and freshwater discharges onto the low tidal zone from the subsurface. These freshwater sources, known as springs, jila (permanent water source) or soaks, are of great cultural value to the Yawuru and other indigenous groups of the Dampier Peninsula. Two of the most interesting are those that illustrate seepage of freshwater into the muddy upper shore zone and the interaction of hinterland groundwater and tidal flat carbonate mud, viz., the seepage lines at the edge of the “pindan” terrain where it borders the mud of tidal flats resulting in linear *Melaleuca* thickets fringing the “pindan”, and the headwaters of scalloped embayments where rivulets discharge surface and groundwater onto/into the tidal flat forming a complex of wetland vegetation. Areas of marked freshwater seepage along the interface of the hinterland and the carbonate mud tidal flats can also be zone of dissolution, resulting in solutional-excavation of the muds and the development of wetland basins.

Keywords: Kimberley Coast, Dampier Peninsula, tropical, coastal wetlands, freshwater seepage

Introduction

Freshwater seepage and freshwater run-off into the coastal zone has important implications for coastal ecology (Semeniuk 1983; Cresswell 2000) and for thousands of years have provided freshwater to the indigenous groups such as the Yawuru, Ngumabal and Jabirrjabirr who inhabited the west coast of the Dampier Peninsula. The springs, freshwater seepages and permanent wetlands, such as Nimalarragan has provided rich biodiversity for these groups. Depending on the climate setting (rainfall), and appropriate aquifers of the hinterland and how they deliver freshwater to the coastal zone, shoreline seepage and surface freshwater inflow can be of low volume, or be quite marked.

The Dampier Peninsula, in the western Kimberley region, residing in a tropical semi-arid monsoon climate has a unique system of freshwater seepage and efflux zones along its western margins. In a shore environment wherein there are tidal flat sediments, salt flats, mangrove formations, and coastal dunes, freshwater is delivered as a surface flow and as subsurface seepages. Interacting with the shoreline deposits, such as dunes and tidal mud, it has generated lagoons and wetlands, and fringing paperbark swamps, respectively.

To date, the styles of freshwater seepage and freshwater inflow have not been described. In particular the significance of the effect of tidal flat muds hydrogeologically on discharge of freshwater from

hinterland aquifers into the marine environments has not been described, but it is an important hydrological feature of the shore leading to the development of specific coastal wetlands.

This paper is an account of freshwater seepages and surfaces flow into the shore zone of the western Dampier Peninsula (or Dampier Land) outlining the geological and stratigraphic framework underpinning freshwater seepages, the types of wetlands and environments produces, and the biological response.

Regional setting

Critical to the understanding of the freshwater seepage and freshwater delivery into the shore zone of the western Dampier Peninsula is the geological framework of the Peninsula, its geomorphology, stratigraphy, climate, and hydrology.

The Dampier Peninsula is a north-trending regional-scale landform whose core is Mesozoic rock (mainly Broome Sandstone) mantled by weathered Broome Sandstone and Quaternary red sand (Brunnschweiler 1957; Geological Survey of Western Australia 1975; Gibson 1983a, 1983b; Gozzard 1988; Fig. 1). The Peninsula is some 170–230 m above sea level along its north to NNW-trending central axis, with elevation decreasing to 20–40 m to north, west, and east towards the coast. The geomorphology of the Peninsula consists of sand plains and linear dunes (often termed “pindan” to refer to the red sand and vegetation complex of this surface) that are dissected by low-gradient, low-relief

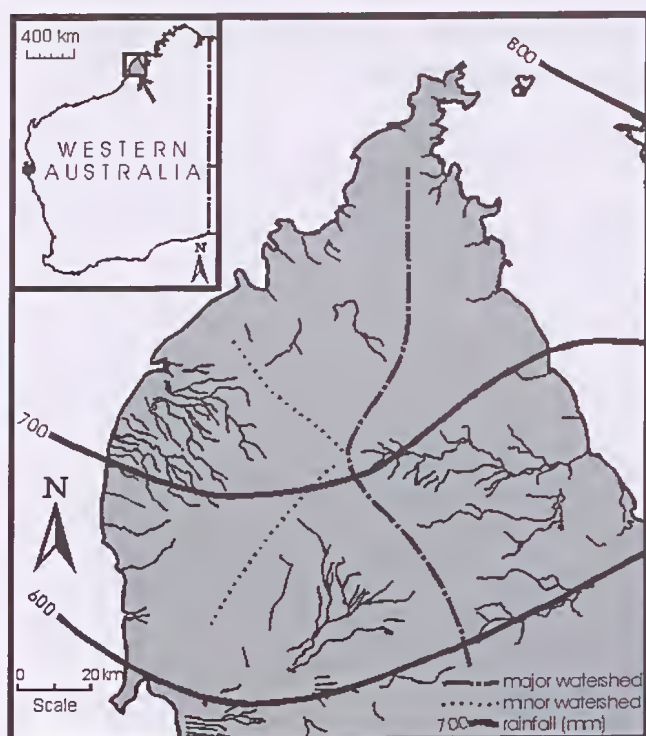


Figure 1. Location of the Dampier Peninsula, showing rainfall isohyets, major and minor watersheds, and main drainage lines that lead to the coast.

streams that have incised through the dune sediments and locally expose Mesozoic rock in their valley tracts. The western coastal zone of the Peninsula consists of mud-filled scalloped embayments, rocky shores cut into Broome Sandstone, shores cut into the red sand, ribbons of coastal dunes, coastal dune and leeward lagoons, coastal dune barriers and leeward mud-filled embayments, shore-parallel limestone, and ribbons of beach rock ramps. Rivulets traversing the Peninsula debouch into the headwaters of the scalloped embayments, or empty into lagoons barred by small barriers, or discharge into the ocean through a (semi-barred) curved outlet.

The stratigraphy of the Dampier Peninsula consists of mainly Broome Sandstone that is overlain by a thin pisolitic to massive ironstone, and a cover of red sand (the Mowanjum Sand; Semeniuk 1980). In the embayments along its west coast there is tidal flat carbonate mud (Sandfire Calcilutite; Semeniuk 2008) which interfingers and grades into the red sand in a zone of muddy sand (Djugun Member; Semeniuk 2008). Also along the coast, abutting or overlying the Broome Sandstone, or cliffs cut into Mowanjum Sand are local outcrops of Pleistocene limestone, shoestrings of Holocene limestone (the Horsewater Soak Calcarene, Kennedys Cottage Limestone and Willie Creek Calcarene; Semeniuk 2008), ribbons and shoestrings of beach and dune sand (Cable Beach Sand and Shoonta Hill Sand, respectively; Semeniuk 2008). These stratigraphic relationships are shown in Figure 2.

The climate of the Dampier Peninsula is tropical semi-arid. Rainfall shows a north to south decrease with ~ 800 mm at Cape Leveque and 600 mm at Broome (Fig. 1).

The rain is highly seasonal, precipitating in the summer months (Gentili 1972; Bureau of Meteorology 1973, 1975, 1988).

The rocks and sediments that comprise the Dampier Peninsula function as aquifers to a range of water bodies. Freshwater resides in the Broome Sandstone (Laws 1990, 1991), with a water table near sea level at the coast and rising inland to form a groundwater mound under the Peninsula (Laws 1990, 1991). At the coast and extending several kilometres inland, the freshwater in the Broome sandstone is underlain by salt water (Laws 1991), the Ghyben-Herzberg interface (Davis & DeWiest 1966). Freshwater also resides in the coastal limestones, and the coastal dunes and, depending on the stratigraphic setting (e.g., the latter is underlain by Sandfire Calcilutite, a whitish calcareous mud known to the Traditional Owners as "kalji"), they may be contiguous with or separate from the regional groundwater residing in the Broome Sandstone. The Mowanjum Sand also stores fresh water that is generally contiguous with the regional groundwater. Salt water resides in the beach sands. As a formation, it is generally near MSL in near-coastal settings and, as such, the aquifer stores freshwater along the dune / tidal flat interface. Salt water, with salinities up to hypersaline, resides in the carbonate mud deposits of the Sandfire Calcilutite within the interval of the formation occurring between mean sea level (MSL) and equinoctial high water spring tide (EHWS). The Sandfire Calcilutite, at its landward occurrences, generally also is a stranded deposit, having formed during a time of higher Holocene MSL (~ 2 m above present MSL), and locally it is weakly (diagenetically) indurated (Semeniuk 2008). These latter aspects of the Sandfire Calcilutite contribute to its impeding freshwater discharge into the coastal zone (see later).

Run-off from the drainage basins on the Peninsula is channelled into a series of streamlines (Fig. 1) and discharges to the coast. However, depending on the nature of the topography of Broome Sandstone and weathered Broome Sandstone where they are buried under the Mowanjum Sand, some channels are open for surface water flows, and some function as buried channels (conduits) for subsurface flows.

Freshwater discharges in the coastal zone

There are range of freshwater discharges in the coastal zone (Fig. 2). There include linear seepage along the edge of the red sand dunes, lakes and soaks at the mouth of rivulets, dune-barred streams forming lakes and sumplands, linear dune seepage onto high tidal zone, and freshwater discharges onto the low tidal zone from the subsurface.

Freshwater in the red sand dunes discharges to seawards, and in a stratigraphic context of carbonate mud onlapping the sand, freshwater flow is impeded by the barrier of relatively impermeable mud (the Sandfire Calcilutite), and discharges to the surface as a spring (Fig. 3A), particularly where the calcilutite is a Holocene stranded deposit, and/or is weakly indurated. The freshwater discharge thus occurs along the contact of the red sand dunes (the "pindan") and high-tidal carbonate mud flats in a linear interface (Fig. 3A) following the

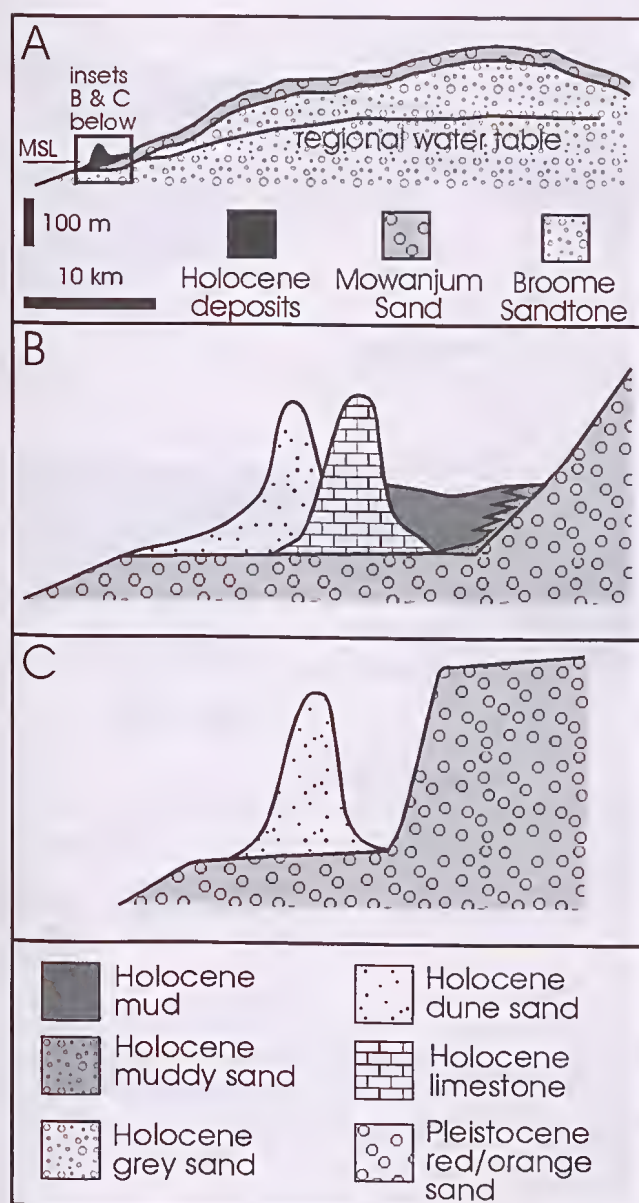


Figure 2. A. Generalised geological cross-section of the Dampier Peninsula showing a base rock of Mesozoic rock and a veneer of Pleistocene Mowanjum Sand (modified after Laws 1990, 1991; Semeniuk 2008). B. Stratigraphic cross-section of a coastal zone where Holocene sand and Holocene limestone bar an embayment filling with Sandfire Calcilutite (modified after Semeniuk 2008). The Holocene units overlie and abut the Pleistocene Mowanjum Sand. C. Stratigraphic cross-section of a coastal zone where Holocene dune sand abuts the Pleistocene Mowanjum Sand (modified after Semeniuk 2008).

edge of the “pindan”. Seepage is facilitated by the muddy sand transition between red sand of the dune fields and carbonate mud (“kalji”) of the tidal flats. Along the interface, the freshwater of the groundwater under the dunes field grades to brackish water under the zone of seepage to hypersaline under the high-tidal parts of the mud flat (Fig. 3B). The vegetation that inhabits this seepage zone consists of *Melaleuca* thickets and forests (mainly *Melaleuca acacioides*), and locally high-tidal mangroves (*Avicennia marina*). In areas of marked seepage, carbonate muds along the interface are dissolved and solutionally-excavated, forming a more permanent (linear) wetland body.

Freshwater in the red sand dunes also discharges to seawards along its contact with coastal dunes. The freshwater discharge occurs along the contact of the red sand dunes and the dunes forming a series of wetland in the swale or depression between the red sand and the coastal dunes. The vegetation that inhabits this seepage zone consists of *Melaleuca* thickets and forests and locally vine thickets.

Rivulets that debouch into headwater of the carbonate-mud-filled scalloped embayments also create zones of wetlands, i.e., lakes and soaks at the mouth of rivulets (Fig. 3C). In these settings, the rivulets have delivered quartzose sand and kaolinitic mud to triangular to fan-shaped high-tidal alluvial fan deposits that interfinger with carbonate mud of the high-tidal flat (Fig. 3C). The freshwater discharge occurs along the rivulet as surface flow during the monsoon season, and as base flow during the dry winter. The flow is impeded by the carbonate mud of the high-tidal flat and surfaces as a spring that is expressed as a permanently waterlogged area (a dampland to sumpland, locally known as a soak), or a lake. The wetland thus formed tends to be, in plan, triangular in shape. Seepage is facilitated by the muddy sand transition between red sand of the dune field, the high-tidal alluvial fan, and the carbonate mud of the tidal flats. Along the interface, the freshwater of the groundwater under the dune field and in the high-tidal alluvial fan grades to brackish water under the zone of seepage to hypersaline under the high-tidal parts of the mud flat (Fig. 3D). The vegetation that inhabits this seepage zone consists of *Melaleuca* thickets and forests (*Melaleuca accacioides*, *Melaleuca cajuputi*), *Pandanus spiralis* associations, and rushlands and sedgelands (with *Schoenoplectus litoralis*), the evergreen tree *Timonius timon*, local Dragon Trees (*Sesbania formosa*), and also, locally, mangrove (*Lumnitzera racemosa*). Similar to the linear seepage zone, in areas of marked discharge, the carbonate muds in the path of the freshwater are dissolved (solutionally-excavated), forming a more permanent (oval to triangular) wetland body.

Streams and rivulets that discharge to the sea have their mouth barred by sand accumulations formed initially by longshore drift, and further barred by coastal dune development (Fig. 3E). These are the dune-barred streams forming impounded lagoons that are lakes and sumplands (Fig. 3F); wetland classification after Semeniuk & Semeniuk 1995. They tend to contain permanent water in the leeward lagoon. The shapes of the water bodies follows the shape of the channel, i.e., they are linear to curvilinear because where the channel has attempted to breach the barrier, the channel has been deflected or curved. Where vegetated, the lagoons support *Melaleuca* thickets and forests, *Pandanus* associations, and rushlands and sedgeland.

The linear dunes of red sand also discharge freshwater under the tidal flats. Fingers of sand, as water-bearing aquifers, lie buried under mud tidal flat, and can convey freshwater to under hypersaline tidal flats. These zones of freshwater discharge remain as subsurface phenomena, but ecologically their presence is manifest as brackish water ecosystems on a high-tidal flat. They are inhabited by *Avicennia marina*, or by copses of *Melaleuca* thickets, or by sedges. Discharge of freshwater into salt flats of eastern King Sound was described by Semeniuk

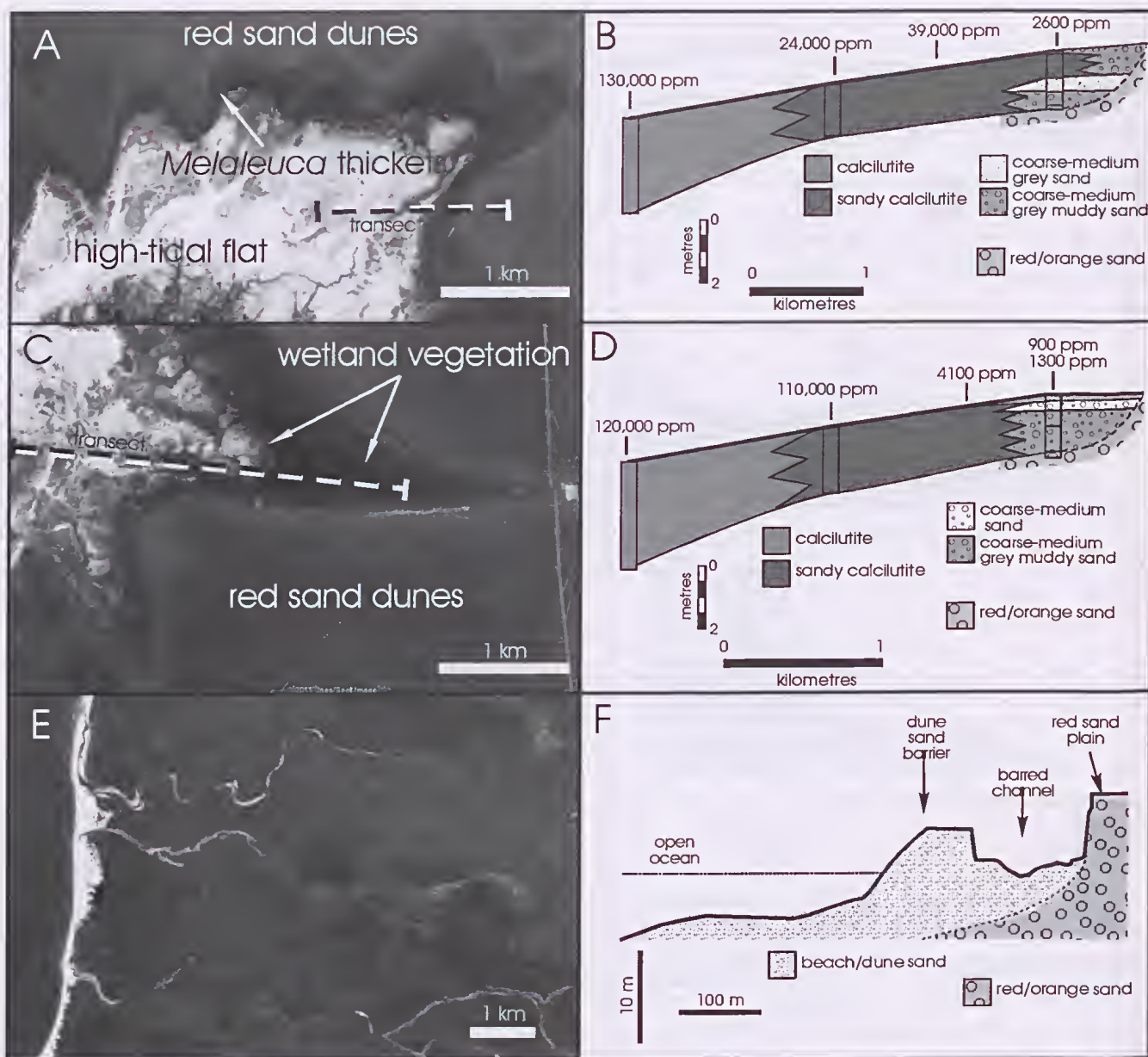


Figure 3. Three locations along the western coast of the Dampier Peninsula showing types of wetland and seepage zones. A. Willie Creek area showing red sand dune terrain, the tidal flats and the *Melaleuca* fringe developed along the zone of seepage. The transect for stratigraphy illustrated in (B) is shown. B. Stratigraphy and groundwater salinity along the transect. C. Willie Creek area showing red sand dune terrain, the tidal flats and the wetland vegetation developed along the contact between a rivulet and the tidal flat. The transect for stratigraphy illustrated in (D) is shown. D. Stratigraphy and groundwater salinity along the transect. E. West coast of Dampier Peninsula showing a range of rivulets (deriving from the terrain of red sand dunes) that are barred by the coastal sand dunes. F. Stratigraphy of area (E) in a transect normal to the coast.

(1980), and similar discharges from linear dunes and local rivulets forming high-tidal wetland, lakes and sumplands occur into the northeastern extremity of the Roebuck Plains, where stranded Quaternary tidal-flat mud adjoins and onlaps the red sand dunes. These locations of seepage are outside the area of study, but similar patterns to these occur along the western Dampier Peninsula.

Freshwater in limestones and in fractured Mesozoic sandstone can discharge onto the low tidal zone from the subsurface. Where there is outcrop of cavernous or microkarst limestone, or fractured sandstone on the low tidal zone (as a rocky shore platform), locally there can

be developed springs of freshwater. These represent freshwater from the hinterland discharging along conduits in the aquifer from the subsurface onto the rocky shore zone.

A summary of the style of freshwater delivery to the coastal zone is provided in Figure 4.

Discussion

The freshwater discharges along the western coast of the Dampier Peninsula are significant from the perspective that these freshwater pockets and ecological

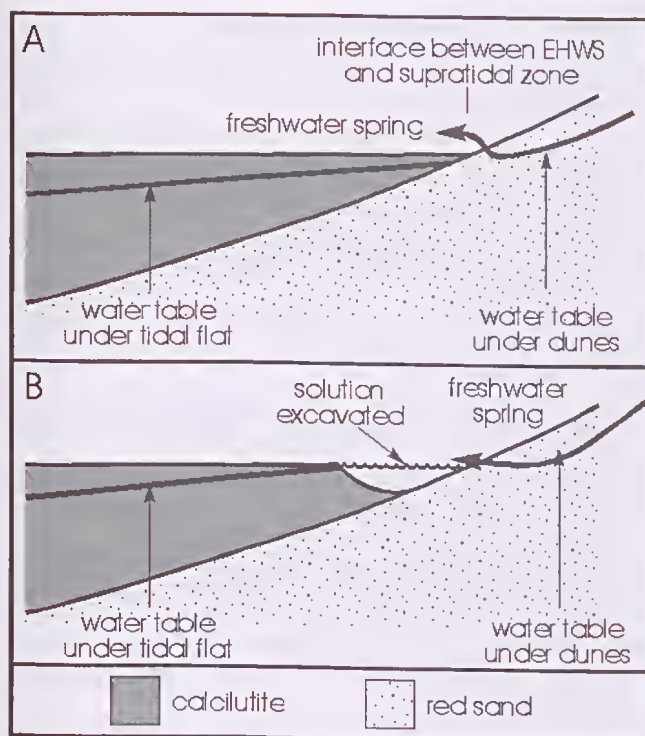


Figure 4. Mechanisms by which freshwater discharge from the red sand dunes forms springs and wetland zones along the contact of Mowanjum Sand and Sandfire Calcilutite. A. The Sandfire Calcilutite impedes freshwater discharge and forms freshwater springs. B. The Sandfire Calcilutite impedes freshwater discharge forming a freshwater spring which solution-excavates a wetland basin.

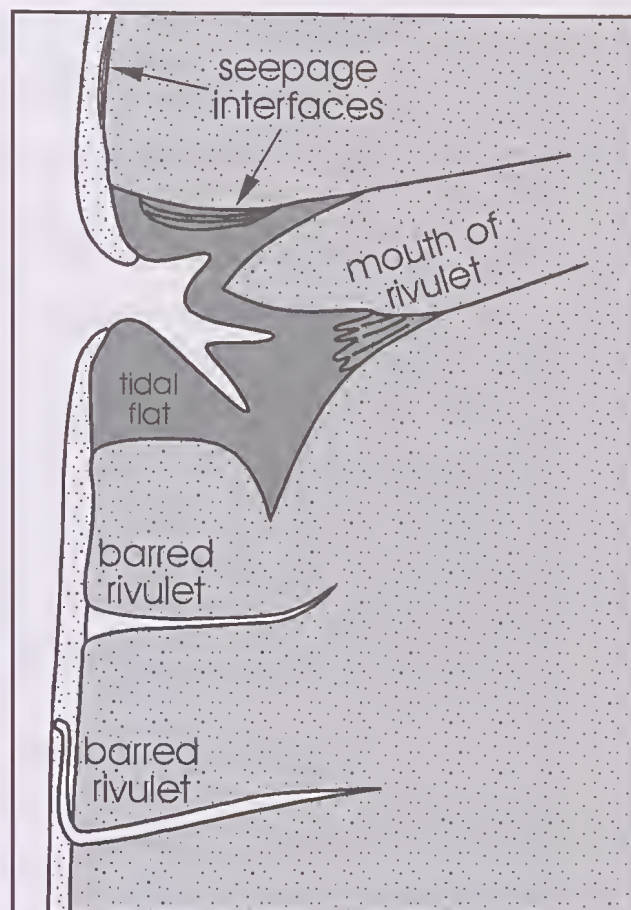


Figure 5. Types of wetlands formed along the coastal zone of the western Dampier Peninsula as a result of stratigraphic and hydrological interaction between the rivulets, Mowanjum Sand, the Sandfire Calcilutite ("kalji") and coastal dunes (Shoonta Hill Sand).

responses to the freshwater occurrences are in a regional setting of tropical semi-aridity. Locally, developed along this zone of freshwater discharge are vine thickets, and in fact the most southern occurrence of vine thickets in Western Australia is along the western Dampier Peninsula (Kenneally *et al.* 1996). Equivalent latitudes in Eastern Australia are humid with rainfall in excess of 1200 mm/pa and 1600 mm/pa, and further south of the Dampier Peninsula, the climate is too arid to support the vegetation and fauna that occurs along any zones of freshwater seepage. In this context, the freshwater seepages and their associated ecological products, particularly in this specific coastal stratigraphic and hydrological setting of red sand dunes and "kalji", are Nationally significant features.

A range of coastal wetlands are developed along the zone of freshwater seepage and the diversity is related to how freshwater is delivered to the coast, into what type of stratigraphic system the discharge takes place, and the characteristics of the stratigraphic units that may be impeding freshwater seepages. As a result there are linear zones of seepage along the edge of the red sand dunes, there are basin wetlands developed along the interface of coastal dunes and red sand dunes, and there are variously barred rivulets. The diagenetic interaction of a marked freshwater seepage zone and "kalji" is of particular interest. Here, solution excavation of the carbonate mud by freshwater results in a deeper basin and in a more permanently inundated wetland.

Various avifauna and other fauna use the wetland developed as freshwater seepages along the shore. The wetlands support a range of avifauna (Rubibi Working Group 1996) including the Purple Swampphen (*Porphyrio porphyrio*), the White-faced heron (*Egretta novahollandiae*), Brolga (*Grus rubicunda*), the Australasian grebe (*Tachybaptus novahollandiae*), the Snipe (*Gallinago* sp), and the Clamorous Reed-Warbler (*Acrocephalus stentoreus*), as well as visiting wading birds such as plovers, avocets, and sandpipers. The more permanent water bodies support freshwater herring (*Nematolosa erebi*), freshwater eel (*Anguilla bicolor*), and barramundi (*Lates calcarifera*).

The wetlands are clearly of National significance and require a careful management. Because of the various stratigraphic and physiographic settings, and the different maintenance mechanisms, the coastal wetlands along this seepage zone, in their variety of wetland expression and vegetation, require a variable management.

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Mangroves of the Kimberley Coast: ecological patterns in a tropical ria coast setting

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Abstract

Mangroves along the Kimberley Coast occupy an unparalleled position globally: they reside in a tropical humid to subhumid climate in the species-rich setting of the Old World Mangroves, and are located along a macrotidal ria shore. This setting provides a range of habitats for mangroves related to larger scale hinterland influences, coastal landforms, coastally expressed geological patterns, shoreline sedimentation patterns, and climate. The mangrove habitats of the Kimberley coast range from rocky (cliff) shores to classic ria shores with tidal flats, tidal creeks, spits, and high-tidal alluvial fans, to rocky-shore-dominated ravines, amongst others. Depending on coastal type, sedimentary setting, and the local species pool, the mangroves form habitat-specific assemblages and characteristic floristic and structural zones within the mangrove formations. The complexity of mangrove habitats and their relationship to the megascale coastal forms of this coastal setting is of international conservation significance.

Keywords: Kimberley Coast, mangroves, mangrove ecology, ria coast, mangrove habitats

Introduction

The Kimberley Coast (Fig. 1) presents a globally unique system of mangroves set in a tropical, (generally) macrotidal environment with variable wave energy. The mangroves therein form floristic, physiognomic, and structural formations that inhabit a wide range of coastal settings from rocky shores to beaches, to large tidal flat expanses, and range from relatively simple assemblages to complex systems. Spanning nearly 900 km from north to south, with ~ 4000 km of coast when measured in intricate detail (Brocx & Semeniuk 2011), the mangroves of the Kimberley Coast exhibit recurring patterns based on coastal form and mangrove habitat. The mangrove diversity within these patterns is determined by a climate that grades from humid in the central Kimberley Coast, to subhumid in a north-easterly direction to semiarid in a south-westerly direction.

There have been several studies that have recorded the mangroves floristically (Semeniuk *et al.* 1978, Bridgewater 1985, Duke 2006), as well as descriptions of mangrove formations in this region in biological surveys (Beard *et al.* 1984, Burbidge & McKenzie 1978; Hnatiuk & Kenneally 1981; Kabay & Burbidge 1977; Miles & Burbidge 1975), descriptions of local assemblages and ecology (Bridgewater 1989; Saenger 1996; Semeniuk 1983, 1985; Thom *et al.* 1975; Wells 1981, 1985, 2006), and descriptions of species distributions (Bridgewater 1982, 1985; Bridgewater & Cresswell 1999, 2003; Duke 1992, 2006; Duke *et al.* 1998; Saenger *et al.* 1977; Semeniuk *et al.* 1978; Semeniuk 1993; Specht 1981; Suzuki & Saenger 1996; Wells 1982). To date, however, there has not been a comprehensive and unifying study of the mangroves of the Kimberley region that explains their biogeographic and site-specific diversity.

This paper is an account of the mangroves of the Kimberley Coast, providing a description of their occurrence in relation to the regional species pool, coastal types, and, most importantly, the expression of habitat-specific assemblages along the coast. The Kimberley Coast has a relatively small regional species pool, a simple climate gradient, and a recurring pattern of coastal habitats, and thus provides an ideal setting to understand mangrove ecology, habitat relationships and biogeography.

To understand the ecological patterns of the mangroves of the Kimberleys it is necessary to examine the mangrove distributions at three hierarchical scales: at the broad regional 'coastal setting' scale; below this at the large scale of 'coastal habitat' within which there are assemblages of habitats; and below this at the finer site specific scale herein termed 'mangrove habitat'. The broadest scale (regional scale) is the form of the coast in the Kimberley region. Below that the 'large' intermediate scale is that at which assemblages of interrelated habitats occur in a given coastal setting. The finest scale is the site-specific mangrove habitat. For this paper, individual physiochemical zones within a mangrove habitat, which often produce the conspicuous zonation of mangrove species, are not treated as habitats. Semeniuk (2011) provides definitions and descriptions for the broad coastal settings that occur along the Kimberley Coast. This paper is structured to describe and explain the regional species pool of the Kimberley Coast from which will be drawn the species that may inhabit a given suite of habitats in the coastal and climate setting for a particular site at particular spatial scales. The scope of this paper and the objective is to provide a broad view of the variety of mangrove habitats and mangrove assemblages that occur in the Kimberley region and relate them to the main abiotic factors of climate, coastal setting, and habitat.

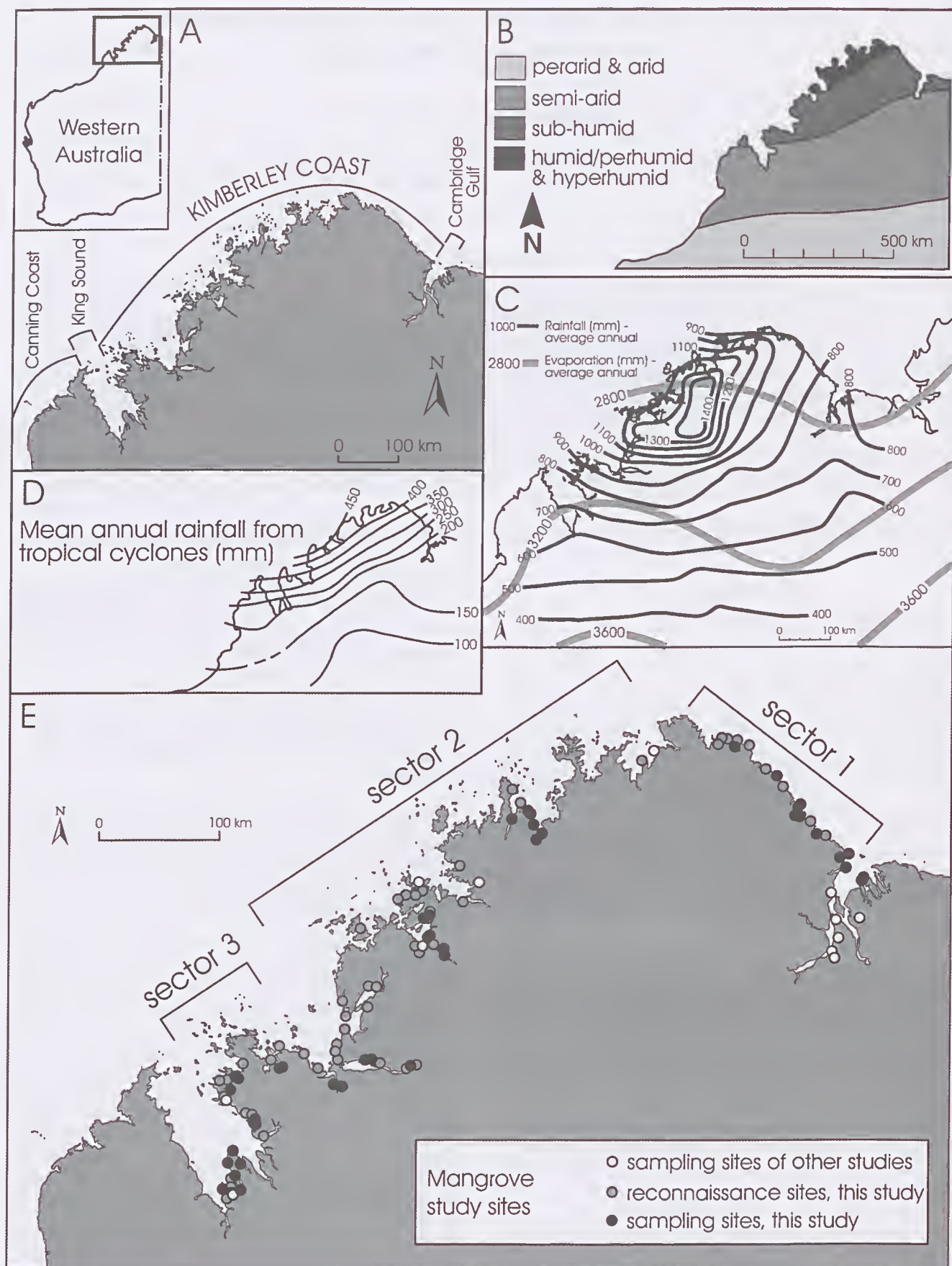


Figure 1. Location, climate and study sites. A. Location of the Kimberley Coast in north-western Australia. B. Climate map after Gentilli (1972). C. Map of rainfall and evaporation (from the Bureau of Meteorology 1973, 1975, 1988, 2010). D. Rainfall from tropical cyclones (after Lourenz 1981). E. Sampling sites this study, reconnaissance sites this study, and sampling sites from other studies.

Methods

The information presented in this paper derives from literature review and fieldwork. A description of the regional to local setting based on the geology, oceanography, tidal regime, climate, geomorphology and some mangrove ecology and biogeography was drawn from the literature and from fieldwork. The description of the geomorphic units and mangrove habitats has been based on extensive fieldwork over more than 40 years, and utilises the existing approach/terminology provided by Semeniuk (1986). In previous years, individual aerial photographs were used, which have been replaced in recent times with the use of satellite imagery and Google Earth, to identify large scale coastal types and finer scale mangrove settings. Field surveys were undertaken to investigate phototones and to describe habitats, substrate type, and mangrove associations and species. Field surveys were conducted over a number of years by road, helicopter, and boat. In general the approach adopted was to identify different "units" using remote sensing and to then ground truth and describe the physical setting and mangrove associations through site visits. At each site, substrate and salinity were noted and stratigraphy determined to ascertain broad compositions of mud, sand, gravel, and rock. Sampling sites in the Kimberley region are shown in Figure 1E.

Previous descriptions of the mangroves of the Kimberley Coast

Thom *et al.* (1975) were the first researchers to describe mangrove ecology in the Kimberley region. They noted the species in the southern Cambridge Gulf area, and described the relative abundance of mangrove species in a series of transects.

Saenger *et al.* (1977) noted the mangrove species across the subcontinent of Western Australia in terms of number of species and their decrease in species richness latitudinally. In describing mangrove distribution in Western Australia, Semeniuk *et al.* (1978) identified four biogeographic zones, assigning the Kimberley region to the zone 'tropic sub-humid'. Galloway (1982), in a description of the entire Australian mangrove coast, assigns the Kimberley area to a single "mangrove region" encompassing Cambridge Gulf, the Kimberley Coast and King Sound. Semeniuk (1983) described the relationship of mangroves to freshwater seepage, and recorded the species in the Kimberley region, and Semeniuk (1985) described mangrove habitats along the ria shorelines of northern Australia, including the Kimberley region, providing a habitat-oriented framework for understanding mangrove ecology. Wells (1985) undertook numerical analyses of mangroves along transects in the Port Warrender and Mitchell River areas, relating species and vegetation structure to riverine setting.

Bridgewater (1985) described the floristic variation along the Western Australia coast noting that "irrespective of local geomorphological differences, complexity of vegetation pattern in the mangal increases in a northerly direction, as a consequence of a greater species richness". He also attempted a phytogeographical analysis, based on the mangal plant communities. His

analysis suggests three zones: temperate, extending north to Shark Bay; dry tropical, from Shark Bay to Cape Keraudren; and wet-dry tropical from Cape Bossut to Cape Hotham in the Kimberleys. Bridgewater noted the three zones correspond in some measure with those of Semeniuk *et al.* (1978). Johnstone (1990) in a study of avifauna habitats described the mangroves of the Kimberley region at 16 sites, noting species, some structure and associations.

Semeniuk (1993) described the mangrove systems of Western Australia, delimiting the Kimberley Coast as a tidally dominated coastal system bordered by two major elements, namely the tide-dominated deltaic systems of King Sound and Cambridge Gulf, and described the shoreline and fluvial inputs which control mangrove systems that occur there, providing examples of the mangrove settings and mangrove habitats present.

Saenger (1996), as part of a marine biological survey of the eastern Kimberley region, described the distribution of mangrove species and habitats. Following Thom *et al.* (1975), Semeniuk *et al.* (1978), Semeniuk (1983, 1985, 1993) and Semeniuk & Wurm (1987), Saenger (1996) described the mangroves and their setting at 17 sites.

Wells (2006) described a fringing vegetation survey of the mangroves undertaken opportunistically as part of another survey in 1977 of five tidal river systems, noting the presence and abundance of 14 vascular species, with some description of the vegetation formations and the salinity profiles of each river system. Following MacNae (1968), Wells (2006) described six habitat zones.

Definition of terms

It is important to define the use of the term "mangrove" to assess what to include or exclude in this paper, as it is a term variably used (MacNae 1968; Chapman 1977; Semeniuk *et al.* 1978; Hutchings & Saenger 1987; Tomlinson 1986, Duke *et al.* 1998). Duke *et al.* (1998), for instance, state that mangrove plants share a number of highly specialized adaptations to allow them to cope with regular inundation by salty waters, and list 39 species occurring in Australia and include ferns, creepers, and herbaceous plants. But use of the term in the literature is inconsistent, and some authors consider herbs in the tidal and shore environment to be mangroves, but exclude creepers and Chenopods. Others include Chenopods but not herbs and creepers/epiphytes. Yet others include all plants occurring in the tidal environment. No single definition has found consistent usage, and hence in this paper we elect to consider only the 'core set' of woody plants that are found within the tidal zone.

The term "mangrove" in this paper refers only to woody trees and shrubs that inhabit tidal environments between mean sea level (MSL) and the highest astronomical tide (HAT). The plants in this zone are anatomically adapted to deal with the tidal inundation, salt water, and anoxic substrate. We believe that in order to understand the biogeography of mangroves, it is necessary to exclude plants that fringe this environment such as samphires (Chenopods), herbaceous plants (e.g., *Acanthus ebracteatus*), ferns (e.g. *Acrostichum speciosum*),

strand plants (e.g., *Hibiscus tilliceus* and *Penphis acidula*), as well as creepers and epiphytes that inhabit the trunks and foliage of any tidal woody plants. Thus we consider that not all plants that inhabit the tidal environment should be viewed as "mangroves". Also, in this paper, the term "mangrove" refers to individual plants inhabiting the tidal zone, while "mangal" refers to the assemblage or community of mangroves.

Definition of the Kimberley Coast based on geology and coastal landform

Following Semeniuk (1993), the Kimberley coastal region is divided into three natural geomorphic units, viz., the Kimberley Coast (the subject area of this paper), King Sound (including Stokes Bay), and Cambridge Gulf (Fig. 1). The Kimberley Coast is the sector centred on the ria shores cut into the Precambrian massif of the Kimberley Basin and Halls Creek Orogen that (onshore) forms the Kimberley Plateau of (mainly) sandstone and (some) basalt (Griffin & Grey 1990a, 1990b). The Kimberley Coast is a rugged, dominantly rocky coastline with local sedimentary accumulations. Its geomorphology is dominated by fracture-controlled medium and short rivers that have incised deep valleys into the sandstone and basalt plateaux of the region. The geological grain, faults, and boundary between geological units (such as between Precambrian massifs and Phanerozoic rocks) have been selectively eroded to form major valley tracts such as the Fitzroy, May, and Meda Rivers.

The regional physical setting: climate, oceanography, and coastal processes underpinning the mangrove distribution and ecology

The Kimberley region is located in a tropical climate, with four climate subregions in terms of rainfall and evaporation (Fig. 1 modified after Gentilli 1972), subdivided into:

1. subhumid in the Cambridge Gulf area and north-eastern Kimberley Coast,
2. humid from Cape Londonderry to Prince Regent River, centred on Port Warrender,
3. subhumid between Prince Regent River and Yampi Sound,
4. semi-arid in the King Sound area.

Coastal rainfall influences local freshwater seepage, as well as the extent that saline high-tidal flats are developed. Evaporation is the other major co-determinant of the extent that high-tidal salt flats are developed. The overall climate, in particular the rainfall in the Kimberley Plateau, determines the extent of run-off into the rivers and the amount of freshwater and sediment delivered to the coastal zone.

The coastal zone of the Kimberley region is subject to four oceanographic processes: semi-diurnal tides, prevailing wind waves, swell, and cyclones.

Tidally, the Kimberley Coast is semi-diurnal, macrotidal with local areas being mesotidal. Tides are

the major defining force along the coast in that they are pervasive regardless of coastal geometry, degree of shelter, and orientation (Semeniuk 2011). The next most important coastal process is wind waves. Where there is enough fetch (oriented in relation to wind directions), wind waves are effective in shaping coastal form and developing mangrove habitats. Wind waves are region-wide but have most influence where headland and coves face the wave direction, or where small islands act as foci for sedimentation. Though a year-round phenomenon, swell impinges on exposed coasts facing northerly to south-westerly sectors, but generally is dampened and refracted as it interacts with the shallowing near-shore shelf, and enters archipelago complexes and fracture-aligned deeply embayed rias. However, swell is not a major wave type in the region.

Cyclones regularly cross the Kimberley Coast on an inter-annual or seasonal basis. They result in highly localised but significant disturbance effects on shores from high seas, large waves and storm surges, and result in winnowing of existing sedimentary deposits, transport and emplacement of sediments at storm levels above and well above the high tide mark, and coastal erosion. They also result in major erosion into mangrove-vegetated tidal flats. The construction of sedimentary deposits above the high-tide mark creates aquifers for freshwater storage that can later discharge freshwater into the high tidal zone to influence vegetation. Also the massive influx of freshwater into the coastal zone during cyclones, results in physical transport of sediment from rivers/creeks to the high-tidal alluvial fans again creating new mangrove habitats, or maintaining high-tidal habitats.

The shores of the Kimberley Coast are highly indented and comprise south-facing, west-facing, and north-facing inlets and embayments, which apart from open gulfs, are mostly isolated from the open sea, being connected only by narrow channels. While most of the Coast is subject to inundation by high tides, storm surges and cyclone-induced high-water, there are many locations protected from swell, wind waves, and storm waves, and in these lower energy environments mangroves are best established.

The coastal processes of sedimentation, tidal erosion, wave action, storms and cyclones, combined with fluvial inputs create the complex habitats of the tidal zone. This region has a dynamic tidal zone not found in most other parts of the world, with massive erosion, or accumulation of sediments. Major cliffs can be cut into tidal mud, tidal channels incised, and sediment dumped into major shoals and creek-mouth fans. Superimposed on this is the longer time-frame of climatic variability in coastal processes, whereby erosion alternates with sedimentation. These processes and sedimentologic and geomorphic adjustments can occur on the small scale or large scale and over varying time frames (cf., Thom *et al.* 1975; Semeniuk 1980; Fig. 2 this paper). The overall outcome of these processes is that mangrove habitats, rather than being an environment reflecting long term geomorphic, hydrologic, and hydrochemical stability, may locally be in flux. Consequently, the vegetation patterns in the mangal of the Kimberley Coast are complex with many differing expressions. For instance the mangal may be truncated, newly colonising recently adjusted surfaces, or in compositional chaos.

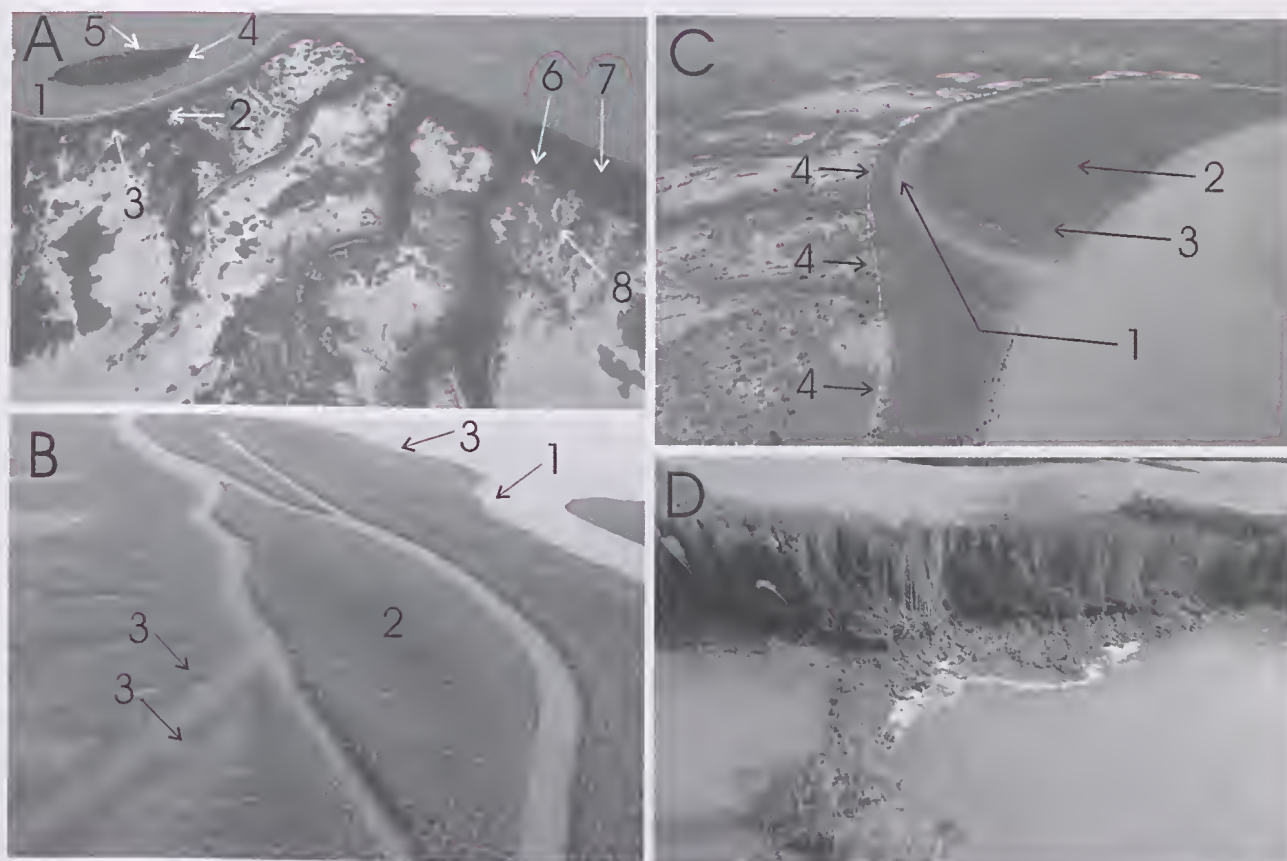


Figure 2. Aerial photographs showing evidence of the dynamic nature of the mangrove environments along the Kimberley Coast. A. Scour and fill and development of shoals: (1) large curvilinear eroded cliffed coast, here outlined by white line; (2) & (3) tidal creeks truncated by the cliffed coast; (4) accreted shoal with mangrove zones parallel to accreted margin; (5) accreted shoal with truncated mangrove zones; (6) former cliff cut into mud abutted by accreted ribbon of mud; (7) zoned mangrove parallel to accreted coast; (8) former history of accretion and erosion and (now) mud-filled tidal creek. B. Recent erosion and shoal development: (1) example of large scale active curvilinear erosion; (2) tidally oriented accreted mud shoal; and (3) examples of smaller scale erosion incising into the mangal. C. Large curvilinear erosional scar (1), with mangrove-vegetated accreted shoal to seaward (2), smaller more recent cliffs cut into the shoal and the mangal (3), and (4) former curvilinear erosional scar (outlined by white line) now stranded by accretion. D. Cliff cutting into mud, with truncation of *Ceriops* thickets.

Landscape, rivers and valleys as architecture to the mangrove habitats

Coastal forms in the Kimberley coastal region have been determined by the lithology and structure of regional geology, interfaces between major geological units, by marine inundation of onshore landforms, and by the sizes, shapes and configuration of rivers, creeks, their tributaries, and other valley tracts in the region, as controlled by geology. The horizontal nature of the lithologies, fault/fractures in the region, and the orogenic fold belts determine the underlying patterns to hinterland landforms and how these are expressed at the coast. Where they crop out along the shore, the rocks in the region define three main sectors of the Kimberley Coast (Fig. 1E):

Sector 1: sandstones of the north-eastern Kimberley coast, with fracture-controlled ravines and short rivers; this sector is the main landscape feature of the north-eastern coastal Kimberley region;

Sector 2: sandstones and basalt between Cape Londonderry and Collier Bay, with fracture-controlled ravines, and short river valleys cut into the sandstone, and more open embayments cut into basalt; this sector is the main landscape feature of the western coastal Kimberley region;

Sector 3: the extension of the King Leopold Orogenic WNW-oriented fold belt – which results in prominent WNW peninsulae (at various scales), inlets and embayments, lagoons, chains of islands, isolated or near-isolated linear high-tidal marine enclosures and, where fracture has influenced cross-oriented drainage, trellis-shaped inlets and embayments; this sector is the main landscape feature of the south-western coastal Kimberley region.

The sedimentary deposits along the Kimberley Coast have been described by Semeniuk (2011). The importance of these deposits is that, apart from rocky shores, a majority form the foundation to mangrove habitats in the region. The distribution of sediments along the Coast at the regional scale is shown in Figure 3. This provides an appreciation of the distribution of mangrove habitats along the Kimberley Coast showing those that are sand-dominated (portions of the coast that face open wave conditions) and that will be associated with barred lagoons, and those that are mud-dominated and occurring in the protected interior of large embayments, or deep embayments, or gulfs.

As noted earlier, an understanding of the distribution of mangroves along the Kimberley Coast requires viewing the system from a subcontinental perspective down to the local setting.

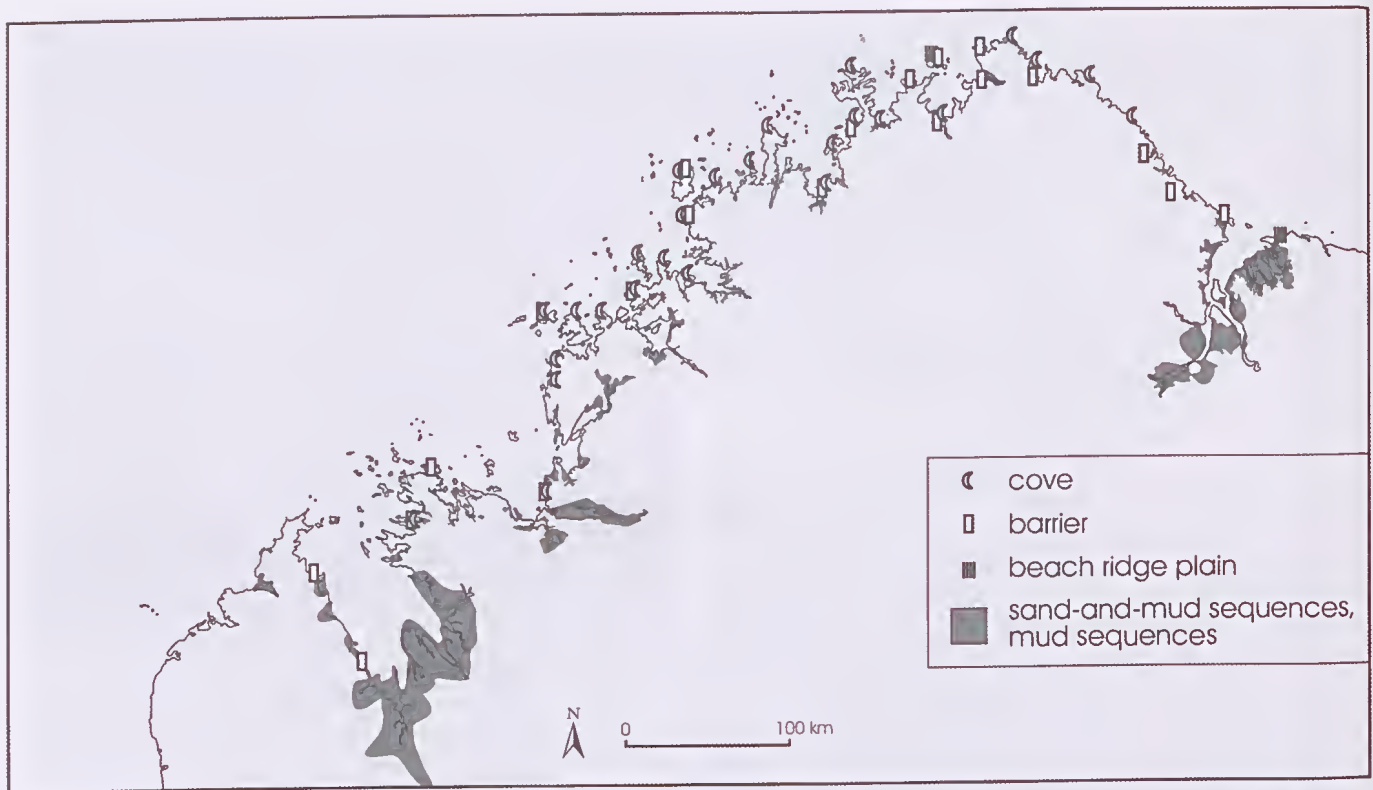


Figure 3. Coastal sediments along the Kimberley Coast (after Semeniuk 2011). The map shows the distribution of sandy coves, sandy barriers, beach ridge plains that are located on the wave exposed open coast, and the sand-and-mud deposits and mud deposits that occur in the interior of embayments and gulfs. The remainder of the coast is largely rocky shore or bouldery shores.

At the regional scale, Semeniuk (2011) describes eleven coastal settings that determine the oceanographic setting of the coast and the style of sedimentary accumulation, and hence which will differentially host mangroves; these are (Fig. 4): 1. large funnel shaped gulfs; 2. large narrow v-shaped gulfs; 3. large broad embayments; 4. medium-sized to small narrow v-shaped ravines and valleys; 5. medium-sized to small embayments and coves; 6. isolated inlets and lagoons; 7. rectilinear to rhomboidal intersecting embayment/inlet complexes; 8. archipelago-and-embayment complexes bordering the Kimberley Plateau; 9. archipelago-and-inlet complexes bordering the King Leopold Orogen; 10. straight rocky shores; and 11. scattered islands in an archipelago.

Depending on the orientation and the oceanographic aspect of these coastal forms, they experience a gradation of wave and tidal energy. They may be exposed to prevailing swell and wind waves and thus subject to

high energy of waves and tides, or may be relatively protected from prevailing wave action and subject mainly to tidal currents, or may be fully protected from wave action and only inundated on the highest tide (slack-water, when mud settles from suspension on the high water). The coastal form, how much of it is subject to waves and tidal currents, and how much sediment is delivered to or generated at the site will determine the style of sedimentary accumulation and the nature of the mangrove habitat that will be developed.

At the large scale setting, the coastal habitats contain assemblages of finest scale mangrove habitats. The large scale coastal habitats identified are: 1. ria embayments; 2. bar-and-lagoon systems; 3. barred ravines; 4. gulfs; 5. tide-dominated deltas; 6. rocky coasts; and 7. beaches. The habitats present within these large scale settings are described in Table 1.

Table 1

Mangrove habitats developed within the large scale coastal habitats.

Large scale setting	Mangrove habitat in general order of abundance and extent
Ria embayments	muddy mid to high-tidal flats, tidal creeks, spits, cheniers, hinterland margin, high-tidal alluvial fan, rocky shore
Bar-and-lagoon systems	muddy high-tidal flats, sandy high-tidal flats, hinterland margin, high-tidal alluvial fan, rocky shore, sandy or gravelly barrier, dune margins
Barred ravines	muddy high-tidal flats, high-tidal alluvial fan, rocky shore, sandy or gravelly barrier
Gulfs	muddy tidal flats, tidal creeks, cheniers
Tide-dominated deltas	muddy tidal flats, tidal creeks, cheniers
Rocky coasts	rocky/bouldery shore, gravelly tidal flats
Beaches	sandy tidal flat, sandy slope

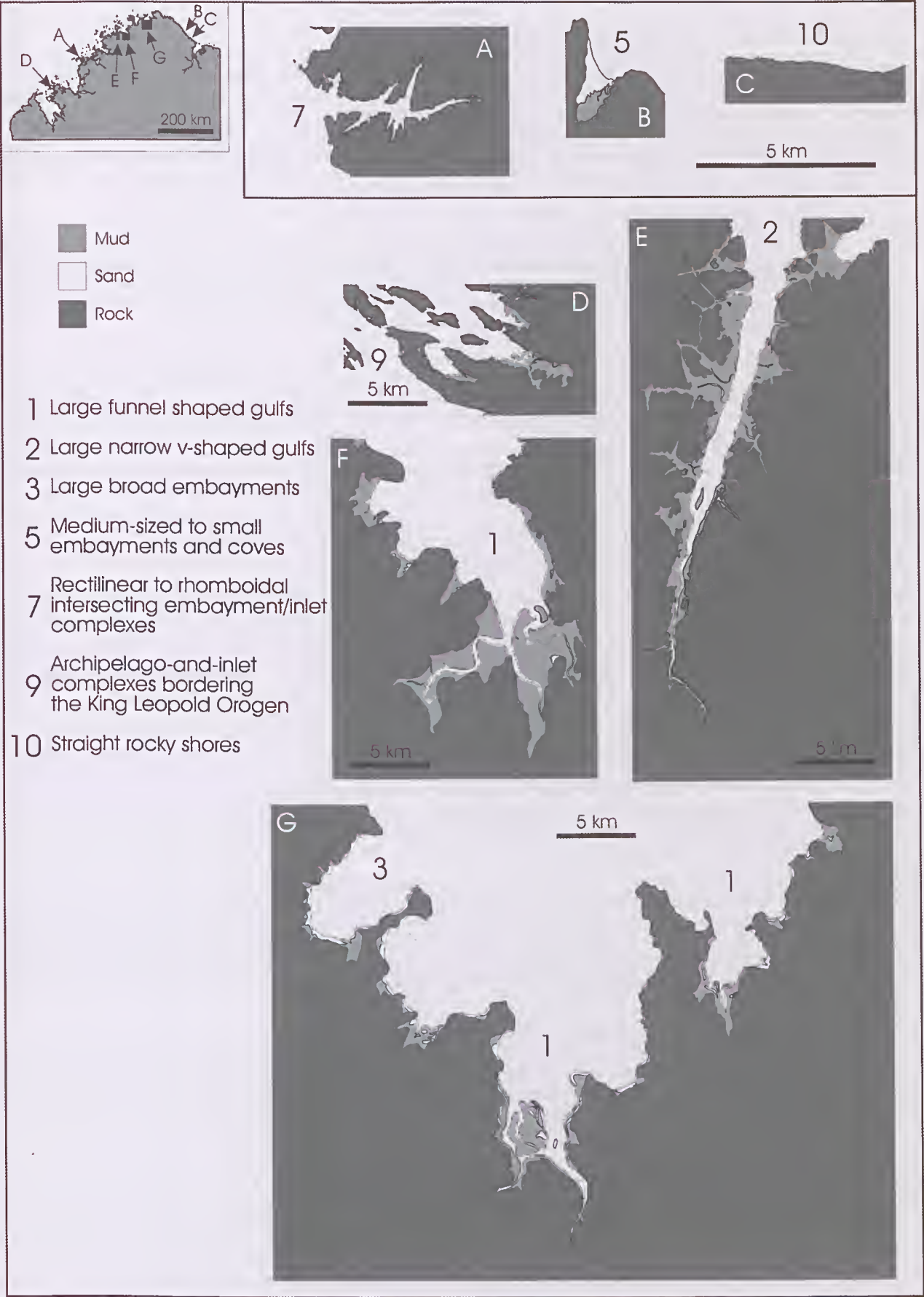


Figure 4. Coastal forms in the Kimberley region that determine (or influence) the nature and style of sedimentary accumulations and determine mangrove habitats (after Brocx & Semeniuk 2011). Bar scale for A, B, C, D, E, F & G is 5 km. The numbering reflects the eleven coastal forms mentioned in the text, and the letters A, B, C, etc. show the location of the example along the Kimberley Coast.

Table 2

Environmental characteristics of the mangrove habitat at the site-specific level

Habitat	Environmental characteristics of the mangrove habitat at the site-specific level
Tidal flat (muddy, sandy, or gravelly)	sloping low-gradient surface underlain mainly by mud, but also may be underlain by muddy sand or sand, or gravel; the surface is inundated by tides, with the mangrove seaward edge at ~ MSL and upper level at HAT; groundwater water salinity at ~ 40,000 ppm at MSL and increasing to 150,000–200,000 ppm at levels above MHWS; above ~ MHWS and salinity of 90,000 ppm, the surface is a salt flat; water table during neap tides usually shallow (< 50 cm); muddy tidal flats are slowly draining, while sandy tidal flats are more rapidly draining
Rocky/bouldery shore	generally moderately to steeply sloping rugged to vertical rocky surface, with shear surfaces, platforms, or fissured, variably covered in boulders, cobbles and pebbles, grading to bouldery shore that is a moderately to steeply sloping surface underlain by cobbles and pebbles; the surface is inundated by tides, with the mangrove seaward edge at ~ MSL and upper level at HAT; groundwater water salinity at ~ 40,000 ppm at MSL and increasing to 100,000 ppm at levels above MHWS; fissured rock is often a source of freshwater seepage discharging to sea and diluting the upper tidal level salinity; groundwater resides in its fracture porosity
Tidal creek bank	generally steeply sloping to vertical rocky surface cut into mud of tidal flat, and underlain by mud, with the mangrove seaward edge at ~ MSL and upper level at ~ MHWN; groundwater water salinity at ~ 40,000 ppm at MSL and increasing to 80,000 ppm at levels of MHWN; because of steep slope, the groundwater drains rapidly, and water table during neap tides is usually deep at bank edge (~ 1m, or > 1 m) grading to shallow (< 50 cm) upslope
Tidal creek point bar	generally low gradient moderately convex surface, underlain by sand, or muddy sand, or mud; mangrove seaward edge at ~ MSL and upper level at ~ MHWN; groundwater water salinity at ~ 40,000 ppm at MSL and increasing to 80,000 ppm at levels of MHWN; water table during neap tides usually shallow (< 50 cm)
Tidal creek shoal	generally low gradient hummocky or moderately convex surface, underlain by sand, or muddy sand, or mud; mangrove seaward edge at ~ MSL and upper level at ~ MHWN; groundwater water salinity at ~ 40,000 ppm at MSL and increasing to 80,000 ppm at levels of MHWN; water table during neap tides usually shallow (< 50 cm)
Hinterland margin	generally low gradient narrow habitat that adjoins the high tidal flat and the hinterland, underlain by muddy gravel, sandy gravel, sand, or muddy sand; mangroves at ~ HAT; groundwater water salinity at hinterland edge variable depending on freshwater seepage (10,000–90,000 ppm) to higher salinity towards salt flat; water table during neap tides usually shallow (< 50 cm); hinterland itself is usually fissured rock and is a source of freshwater seepage discharging to sea and diluting the upper tidal level salinity; groundwater resides in hinterland bedrock in its fracture porosity
High-tidal alluvial fan	generally low gradient triangular to fan shaped habitat that adjoins the high tidal flat and the hinterland in the headwaters of an embayment; underlain by muddy gravel, sandy gravel, sand, or muddy sand; mangroves at ~ HAT to MHWS; groundwater water salinity at hinterland edge variable depending on freshwater seepage (1000–10,000–90,000 ppm) with higher salinity towards salt flat; water table during neap tides usually shallow (< 10 cm); rivulet or small stream is the source of the sediment that underlies the alluvial fan and is the source of freshwater seepage discharging to sea and diluting the upper tidal level salinity; the habitat and its vegetation may grade upslope above HAT into freshwater wetland habitats
Beaches	moderately sloping surface underlain by sand or shelly sand; the sloping surface is inundated by tides, but the upslope part may be emergent above the level of HAT with development of dunes; mangrove seaward edge at ~ MSL and upper level at MHWS; groundwater water salinity at ~ 40,000 ppm at MSL and increasing to 60,000 or 70,000 ppm at levels above MHWS; the dune hinterland or the bedrock hinterland that adjoins the beach, occurring above HAT, stores freshwater or brackish water that discharges to seaward and dilutes the groundwater salinity that is under the tidally inundated beach slope; water table during neap tides on slopes of beach usually shallow (< 50 cm), but may be up to 1 m deep
Spits	Convex bar or finger of sediment underlain by sand or gravel, or gravelly sand, emanating from a headland; margins of the spit are sloping low-gradient surfaces; the sloping surfaces are inundated by tides, but the crest may be emergent above the level of HAT; mangrove seaward edge at ~ MSL and upper level at MHWS; groundwater water salinity at ~ 40,000 ppm at MSL and increasing to 60,000–70,000 ppm at levels above MHWS; the core of the spit, particularly if emergent above HAT, stores freshwater or brackish water that discharges to seaward and dilutes the groundwater salinity that is under the tidally inundated spit margin; water table during neap tides on slopes of spit usually shallow (< 50 cm)
Cheniers	convex bar or finger of sediment underlain by sand or gravel, or gravelly sand, but isolated on the tidal flat, often surrounded by salt flat; margins of the chenier are sloping low-gradient surfaces; the sloping surfaces are inundated by tides, but the crest is emergent above the level of HAT; mangrove seaward edge at ~ MHWS and upper level at HAT where there is fresher-water discharge; groundwater water salinity at ~ 70,000–90,000 ppm at MHWS and decreasing to 10,000 ppm at levels above MHWS; the core of the chenier, particularly if emergent above HAT, stores freshwater or brackish water that discharges to seaward and dilutes the groundwater salinity that is under the tidally inundated chenier margin; water table on slopes and margins of chenier during neap tides usually shallow (< 50 cm)

Table 2 (cont.)

Habitat	Environmental characteristics of the mangrove habitat at the site-specific level
Barriers	similar to a spit, but the sedimentary body fully bars the entrance to an embayment; the barrier is a convex bar or finger of sediment underlain by sand or gravel, or gravelly sand, bridging the headland of an embayment; margins of the barrier are sloping low-gradient surfaces; the sloping surfaces are inundated by tides, but the crest is emergent above the level of HAT; mangrove seaward edge at ~ MSL and upper level at MHWS; groundwater water salinity at ~ 40,000 ppm at MSL and increasing to 60,000 or 70,000 ppm at levels above MHWS; the core of the barrier stores freshwater or brackish water that discharges to seaward and dilutes the groundwater salinity that is under the tidally inundated spit margin; water table on slopes of barrier during neap tides usually shallow (< 50 cm)
Dune margin	generally low gradient narrow habitat that adjoins supratidal sand dunes, underlain by sand or muddy sand; mangroves at ~ HAT; groundwater water salinity at dune edge variable depending on freshwater seepage (10,000–90,000 ppm) increasing to higher salinity towards salt flat; water table during neap tides usually shallow (< 50 cm); dune sands are a source of freshwater seepage discharging to sea and diluting the upper tidal level salinity

The finest site-specific mangrove habitat scale (after Semeniuk 1985, 1993) in general order of abundance and extent of mangrove cover, are: 1. tidal flat; 2. rocky/bouldery shore; 3. tidal creek bank; 4. tidal creek point bar; 5. tidal creek shoal; 6. hinterland margin; 7. high-tidal alluvial fans; 8. beaches; 9. spits; 10. cheniers; 11. barriers; and 12. dune margin.

Within each habitat there are gradients of environmental conditions (decreasing tidal inundation, increasing groundwater salinity, decreasing groundwater salinity towards sources of freshwater, or progressive change in sediment grain size). In response to these gradients and their combinations along the habitat slope, zonation of mangrove species takes place across a given habitat. Environmental characteristics that are important to mangroves at the site-specific habitat level are described in Table 2.

Distribution of mangroves in the Kimberley region (the regional species pool)

Determining the occurrence and distribution of mangrove species in the Kimberley region, whether through the literature, herbaria records, or field work (in order to determine what might be present in a given coastal sector) is difficult for several reasons:

1. species do not occur consistently within an environmental setting;
2. not all species will be present in a given locality even if (apparently) appropriate habitats are present;
3. species richness progressively decreases along the coast from the species-rich northern Australia to the Kimberley Coast, and locally increases in the Kimberley region in relation to subregional increase in rainfall; and
4. the "regional species pool" is not well delineated or determined due to incomplete literature both in terms of geographic scope and sampling.

In the first instance, use of the literature to determine where mangroves occur is not reliable, as the records of species occurrences are related to type and effort of sampling. For example, consider the species recorded to

date in the Point Walsh, Port Warrender area: Semeniuk (1985) records thirteen species of mangrove (*Avicennia marina*, *Aegialitis annulata*, *Aegiceras corniculatum*, *Bruguiera exaristata*, *Bruguiera parviflora*, *Camptostemon schultzei*, *Ceriops tagal*, *Excoecaria agallocha*, *Lumnitzera racemosa*, *Osbornia octodonta*, *Rhizophora stylosa*, *Sonneratia alba*, and *Xylocarpus* sp) while Johnstone (1990) records only eleven species (with *Bruguiera parviflora* and *Lumnitzera racemosa* not recorded). The mangroves recorded by Semeniuk (1980, 1983) at Stokes Bay and at Derby total eleven and ten species, respectively (*viz.*, *Avicennia marina*, *Aegialitis annulata*, *Aegiceras corniculatum*, *Bruguiera exaristata*, *Camptostemon schultzei*, *Ceriops tagal*, *Excoecaria agallocha*, *Osbornia octodonta*, *Rhizophora stylosa*, and *Xylocarpus moluccensis*; with *Bruguiera parviflora* at Stokes Bay only) while Johnstone records only six species. Using the information in Johnstone (1990) would distort the picture of the regional species pool in that the local biodiversity at Port Warrender would be underestimated and the southern extensions of key species (such as the occurrence of *Bruguiera parviflora* at Stokes Bay) would be missing.

Similarly a comparison between Thom *et al.* (1975), Johnstone (1990) and Saenger (1996) of the number of mangrove species in the general Cambridge Gulf region, shows variation in species richness due to sites visited, taxonomic changes, habitats sampled, and sampling effort. Thom *et al.* (1975), in the general Cambridge Gulf region record seven species, Johnstone (1990) in the southern Cambridge Gulf region records nine species, and Saenger (1996) in the northern Cambridge Gulf region records eleven species. In the Cape Domett area of northern Cambridge Gulf, Thom *et al.* (1975) record three species, while Saenger (1996) in the northern Cambridge Gulf region records ten species.

The variation in survey results, in part, reflects ecological variation. *Sonneratia alba*, for example, a mangrove that commonly occupies the seaward fringe, does not always occur in this seaward location/habitat, rendering difficult the characterisation of the regional species pool by literature review and herbaria records. Similarly, the preferred habitats for some species are not consistently developed from site to site and the species will be locally absent, again rendering difficult the characterisation of the regional species pool by literature review and herbaria records.

Surveys of mangroves often concentrate on the main shore-parallel stands of mangroves, with documentation of zonation, and here *Sonneratia alba*, *Avicennia marina*, *Rhizophora stylosa* and *Ceriops tagal* will be the most obvious, and thus recorded. But unless the researchers have traversed the mangroves in a number of transects, any understorey of low abundance and scattered species, *Aegialitis annulata*, for instance, may be missed, and if there is no focus specifically on shore-transverse tidal creeks, *Aegialitis annulata*, *Aegiceras corniculatum* and *Camptostemon schultzei* may also be missed.

Figure 5 illustrates the principle of variability of mangal composition depending on sampling location and habitat complexity. In this example a shore-normal, elongate, small island (with a seaward bouldery shore) acts as an anchor for a sandy tombolo. There are several mangrove habitats present: a rocky shore, bouldery shore, a shore-normal sandy tombolo (equivalent to a high-tidal spit), a gravelly tidal flat, muddy tidal flat, hinterland margin, and a sand spit (located in the middle extreme right of the image). The mangrove habitat at approximately MSL varies from right to left, which is reflected in a change in mangal composition from a *Sonneratia* and *Avicennia* association and an upper slope occurrence of *Rhizophora* on right and left flanks to dominantly an *Avicennia* stand in the central seaward area. *Rhizophora* is most abundant and forms a dense copse on the left side of the tombolo. The mangal fringing

the tombolo is asymmetric in its composition, with *Avicennia*, *Ceriops*, and *Bruguiera* forming denser formations on the left flank. There is mangal fringing the sand spit. The sand spit also is a reservoir for freshwater, which discharges in a series of (six) small "rivulets" that are inhabited by mangrove shrubs.

As mentioned above, researchers tend to focus on the main mangrove stand, documenting the species in the shore-parallel zonation, but the minor landward fringe comprised of scattered shrubs, the headwaters of ria embayments, and margins of spits and cheniers (where again there are only fringing narrow stands of scattered shrubs) may not be examined. It is in these latter locations that *Ceriops tagal*, *Excoecaria agallocha*, *Lumnitzera racemosa*, *Scyphiphora hydrophyllacea* and *Xylocarpus moluccensis* occur (as well as the other species considered by other authors to be mangroves, viz., *Acanthus ebracteatus* and *Peumphis acidula*), and if there is to be a robust analysis of the progressive change in the regional species pool against climate gradients and local habitats, these latter habitats would need to be systematically examined.

The records of mangrove species along the Kimberley Coast in the literature, and indeed the sparse records lodged as specimens in herbaria (see Fig. 6) are not reliable sources of information to establish occurrences of species in the region, or even whether a given species occurs at a given site, due to the limited sampling effort



Figure 5. Oblique aerial photograph illustrating the variability of mangal composition along and across the shore in relation to habitat type, substrates, tidal levels, and freshwater seepage (see text for more detailed description).

and method carried out along the Kimberley coastal region to date, the patchiness of species occurrence, the serendipitous nature of the occurrence of some species, and the habitat-specific nature of other species. Yet, this type of information is fundamental to assessing change in biodiversity of mangroves gauged against various parameters of the climate gradient and freshwater seepage. The surveys of mangroves in the northern and north-eastern Kimberley area by Saenger (1996) illustrate the problems of opportunistic and *ad hoc* collecting, sampling without a habitat framework (as distinct from identifying the habitat type at the sampling site), and the difficulties in determining an inventory of the regional species pool that would form the foundation to determining and predicting the habitat-specific biodiversity. Notwithstanding logistic difficulties such as the pressure of lack of time as a factor in sampling effort, variations in records of species can result from how the mangrove surveys are approached. Researchers surveying by boat tend to access the mangroves from the seaward edge, usually on a mid-tide, and have to traverse thick stands of mangroves to sample within the mangal and to sample the hinterland fringe or the high-tidal alluvial fans. As a result, usually only one traverse might be made, and the hinterland fringe is often not fully surveyed. Researchers accessing the shore by road tend to access the mangroves from the landward edge, and may have to traverse thick stands of mangroves to sample the seaward fringe. As a result, for land-based surveys, the hinterland fringe, high-tidal alluvial fans, rocky shores, and spits may be reasonably sampled, but variations in the main mangrove stand, especially the occurrence of understorey species, such as *Aegialitis annulata*, or patchy copses of *Osbornia octodonta*, may be missed.

Remote sensing (aerial surveys, aerial photography, satellite imagery) enables researchers to note the general zonation and distribution of species in a mangrove system. Low-altitude aerial surveys allow, at best, identification of key species such as *Sonneratia alba*, *Avicennia marina*, *Rhizophora stylosa*, *Ceriops tagal*, *Lumnitzera racemosa*, *Camptostemon schultzei*, and *Xylocarpus moluccensis*, but do not allow for identification of understorey species or between species of *Bruguiera*. Helicopter surveys allow for closer-to-ground flight paths, and hovering, and hence clearer identification of key species from low-altitudes, and also allow for landings whereby specific trees of a given height, physiognomy, or canopy colour can be differentiated (e.g., the species of *Bruguiera*, or the species of *Xylocarpus*). Generally the similar morphology and leaf 'greenness' makes it very difficult to accurately attribute species with remote sensing.

The habitat-directed approach adopted by Semeniuk (1985) and Semeniuk & Wurm (1987), wherein every habitat is identified and sampled, provides a systematic method of determining the species pool at a given site because species often form assemblages related to habitat, or tend to prefer specific habitats (e.g., *Osbornia octodonta* is commonly found on sandy beaches where there is beach rock, *Lumnitzera racemosa* is commonly found along the hinterland fringe, and *Camptostemon schultzei*, *Aegialitis annulata*, and *Aegiceras corniculatum*, singularly or collectively, are commonly found along tidal creek

banks). With this approach, sampling all habitats in a given locality is likely to capture all the mangrove species occurring at that locality and the absence or presence of a given species can be assessed in context.

While sampling style and effort will determine whether a given species is recorded in an area, in some locations habitats may not be developed, so particular species will be absent from the site. Conversely, other natural processes may preclude some species even though their preferred habitat is present. Also, very local and recent coastal history of erosion and sedimentation may result in the elimination of characteristic zonation and predictable occurrence of species and, instead, is replaced with an (erosionally) truncated zonation (Fig. 2D), or with a chaotic mixture of species (as the environment adjusts to an altered and dynamic hydrology and hydrochemistry).

Given these complications, nonetheless, we have endeavoured to provide an overview of the mangroves of the Kimberley region from a perspective of species distribution to determine what species are available locally to colonise the various habitats of the Kimberley Coast. To achieve this, we note the occurrence of a given species in tropical humid northern Australia as recorded in the literature, and its most southern occurrence in Western Australia. We have then presumed that the biogeographic range of the target species will encompass the most northern localities in Western Australia as well as its most southern localities, with confirmation of sites between these two extremes from records in the literature. Following this, site-specific occurrences and habitat-specific occurrences of any given species, and habitat-specific assemblages are drawn from this "regional species pool". If a species is absent at a given location, but is within its biogeographic range, this may be due to climate setting, lack of habitat, or the local history of erosion and sedimentation, amongst other factors.

Overall, with the exclusion of *Acanthus ebracteatus* and *Pemphis acidula*, there are 15 species of mangroves along the Kimberley coast, though they are not present consistently and ubiquitously throughout the region. For this paper, the entire Kimberley region is treated as the one regional species pool, with local climate and habitat factors selecting for mangroves species that will occur at a given site. In order of general abundance and relatively consistent occurrence through the region, the species are placed in three groups: generally abundant and consistently present; generally present, though not abundant and consistently present; generally not abundant nor consistently present. The composition of these groups are:

1. Generally abundant and consistently present: *Avicennia marina*, *Rhizophora stylosa*, *Ceriops tagal*, *Sonneratia alba*, *Camptostemon schultzei*, *Aegialitis annulata*, *Aegiceras corniculatum*, *Bruguiera exaristata*, *Lumnitzera racemosa*, and *Excoecaria agallocha*.
2. Generally present, though not abundant and consistently present: *Bruguiera parviflora*, *Osbornia octodonta*, and *Xylocarpus moluccensis*.
3. Generally not abundant nor consistently present: *Scyphiophora hydrophyllacea* and *Xylocarpus granatum*.

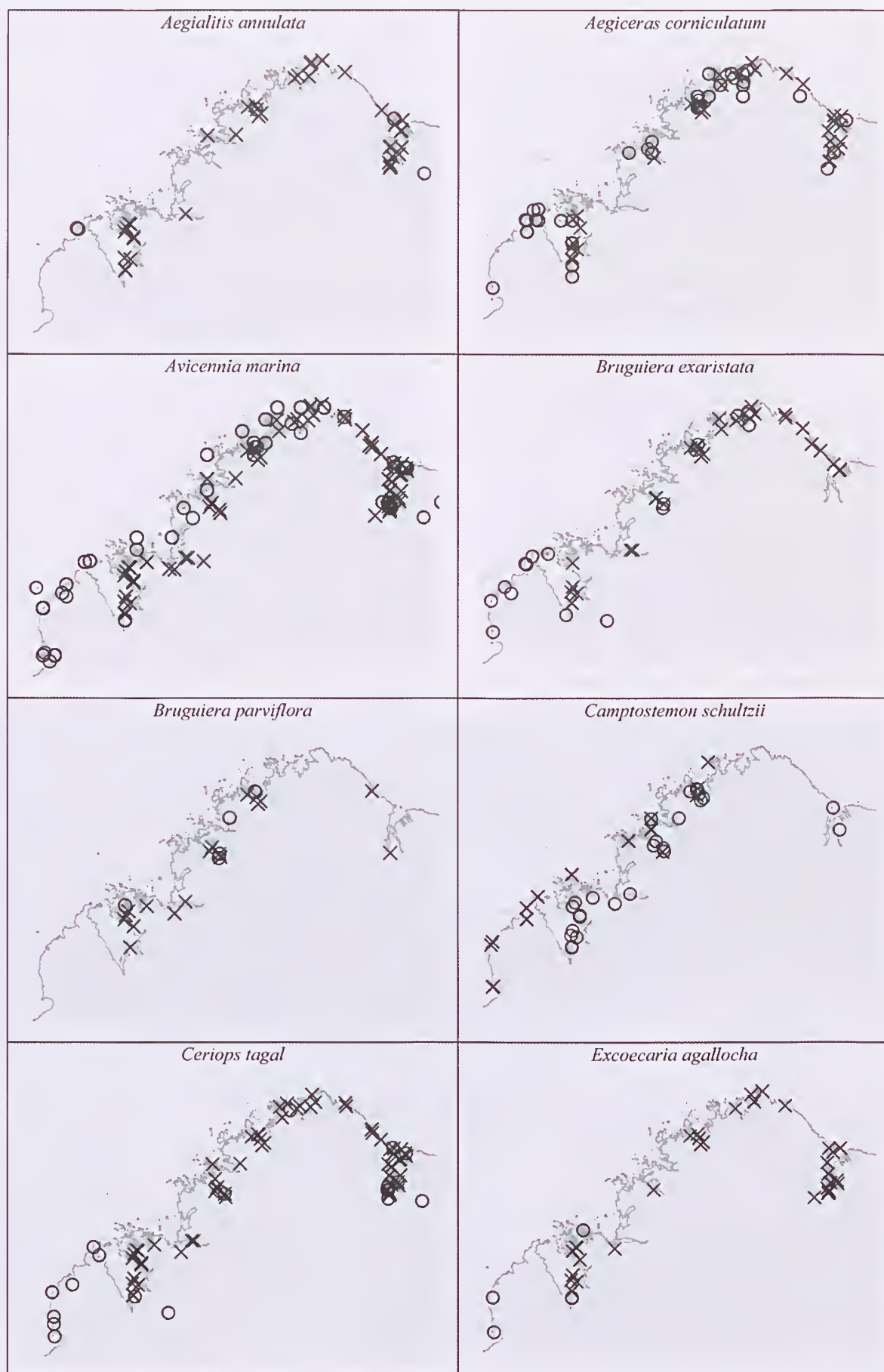


Figure 6. Distribution of the key species of mangroves according to herbaria records (via Atlas of Living Australia), studies by other authors as mentioned in the text, and our studies.

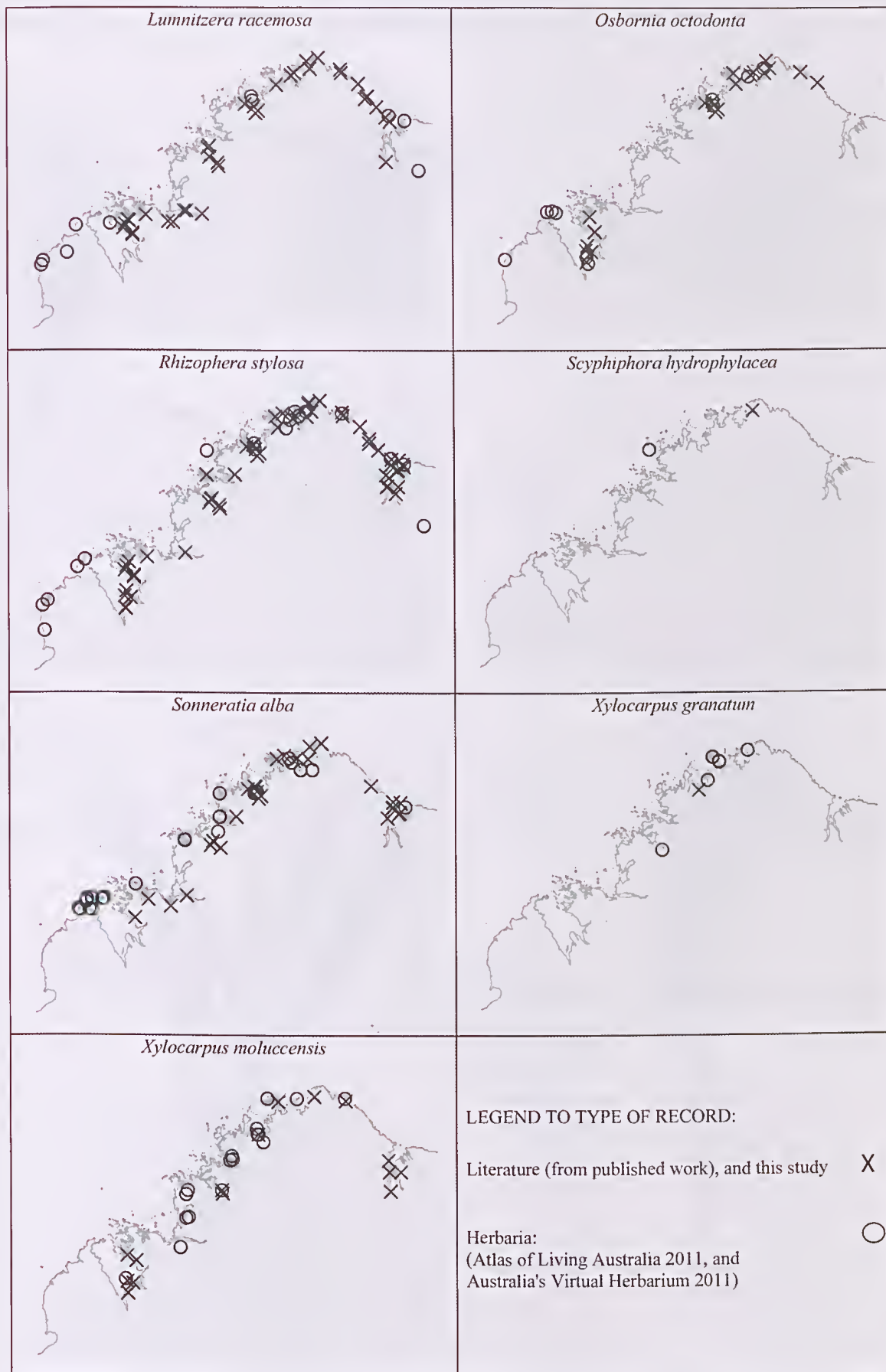


Figure 6 (cont.)

Avicennia marina, *Rhizophora stylosa*, and *Ceriops tagal* are the most common and ubiquitous species in the region. [*Avicennia eucalyptifolia* listed in Thom *et al.* (1975) and Semeniuk *et al.* (1978) has been taxonomically re-assigned to a variety of *Avicennia marina* (Duke 2006). The varieties of *Avicennia marina* are not distinguished in this paper.]

Overview of the distribution of mangrove species in the Kimberley region determined by regional abiotic factors

There are two major gradients that determine species richness along the Kimberley Coast: 1. the general decline in species richness towards the Kimberley from the species-rich humid northern Australian region; and 2. the climate gradient *within* the Kimberley region.

In the first instance, mangrove species richness decreases from the species-rich humid northern Queensland coast and the humid Darwin area (where there are some 39 species and 31 species of mangroves, respectively (Duke (2006)) to the Kimberley region, where there are less than 20 species (using our definition there are only 15 species). As noted earlier, there is a climate gradient *within* the Kimberley region from subhumid and semiarid in the Cambridge Gulf and King Sound areas, respectively, to humid in the central Kimberley Coast, with an increase in mangrove diversity towards this humid centre. From humid northern Australia to mid-western Western Australia, the limits of key species are listed in Table 3.

Of these 15 "core" species of mangroves in the Kimberley Coast region, *Xylocarpus granatum* is localised in the humid Port Warrender region, and *Scyphiphora hydrophyllacea* extends from northern Australia to the Drysdale River region only. The distribution of mangrove species in the Kimberley region is shown in Figure 6.

Mangrove assemblages along the Kimberley Coast with respect to habitats

As noted above, 15 mangrove species are regionally widespread and available to inhabit the various coastal types and appropriate habitats. Thus habitats will, to a large extent, determine the species of mangrove that will occur in a site-specific area, with colonisation underpinned by the driving factors of tidal level, substrate types, hydrology, prevailing soil moisture, salinity, freshwater seepage, and air temperature. Aspects of habitats and the occurrence of habitats as suites within a coastal setting are illustrated and explained in Figures 7–10. Figure 7 shows the most common coastal settings in the region and the suites of habitats that occur within them. Figures 8 and 9 show the habitat elements of ria embayments and the mangroves inhabiting them. Figure 10 shows a suite of habitats within a ria embayment and the hydrological/hydrochemical mechanisms maintaining the mangroves. Aerial photographs of typical habitats and mangals along the Kimberley Coast are illustrated in Figures 11 and 12.

While species such as *Avicennia marina* can be inundated for up to 6 hours a day, survive salinities of up to 90,000 ppm, and inhabit substrates of rocky shores, sand, or mud (as such, it is the species that is most widespread across a variety of habitats), various other mangrove species clearly are adapted to different and specific environments in the tidal zone. *Scyphiphora hydrophyllacea*, for instance, inhabits the highest tidal zone along hinterland margins with freshwater seepage, and is not found in the main belt of mangroves, and certainly not at the seaward fringe. *Camptostemon schultzei* preferentially inhabits muddy tidal creek banks, where it is inundated for several hours a day, but where tidal creek banks rapidly drain tidal groundwater.

While the combination of environmental conditions suitable for a given species to survive can be created in a

Table 3

Limits of mangrove species latitudinally/longitudinally in Western Australia

Species	Most southern or western occurrence	Coordinates
<i>Scyphiphora hydrophyllacea</i>	Drysdale River	14°12'28.99"S 126°38'36.23"E
<i>Xylocarpus granatum</i>	Port Warrender	15°17'54.65"S 127°17'24.57"E
<i>Bruguiera parviflora</i>	Stokes Bay	35°37'46.44"S 137°12'12.55"E
<i>Camptostemon schultzei</i>	Broome	17°57'43.62"S 122°14'10.05"E
<i>Lumnitzera racemosa</i>	Broome	17°57'43.62"S 122°14'10.05"E
<i>Xylocarpus moluccensis</i>	Broome	17°57'43.62"S 122°14'10.05"E
<i>Sonneratia alba</i>	Cape Bossut	18°43'0.00"S 121°37'60.00"E
<i>Excoecaria agallocha</i>	De Grey River delta	20°18'7.53"S 119°15'58.50"E
<i>Osbornia octodonta</i>	Cossack	20°18'7.53"S 119°15'58.50"E
<i>Aegiceras corniculatum</i>	Maitland River delta	21°13'40.84"S 116°53'6.77"E
<i>Bruguiera exaristata</i>	Maitland River delta	21°13'40.84"S 116°53'6.77"E
<i>Ceriops tagal</i>	Exmouth Gulf	22°53'34.40"S 114°31'22.27"E
<i>Aegialitis annulata</i>	Exmouth Gulf	21°13'40.84"S 116°53'6.77"E
<i>Rhizophora stylosa</i>	Yardie Creek and Exmouth Gulf	22°28'32.22"S 113°57'9.07"E
<i>Avicennia marina</i>	Bunbury	33°19'37.44"S 115°38'21.03"E

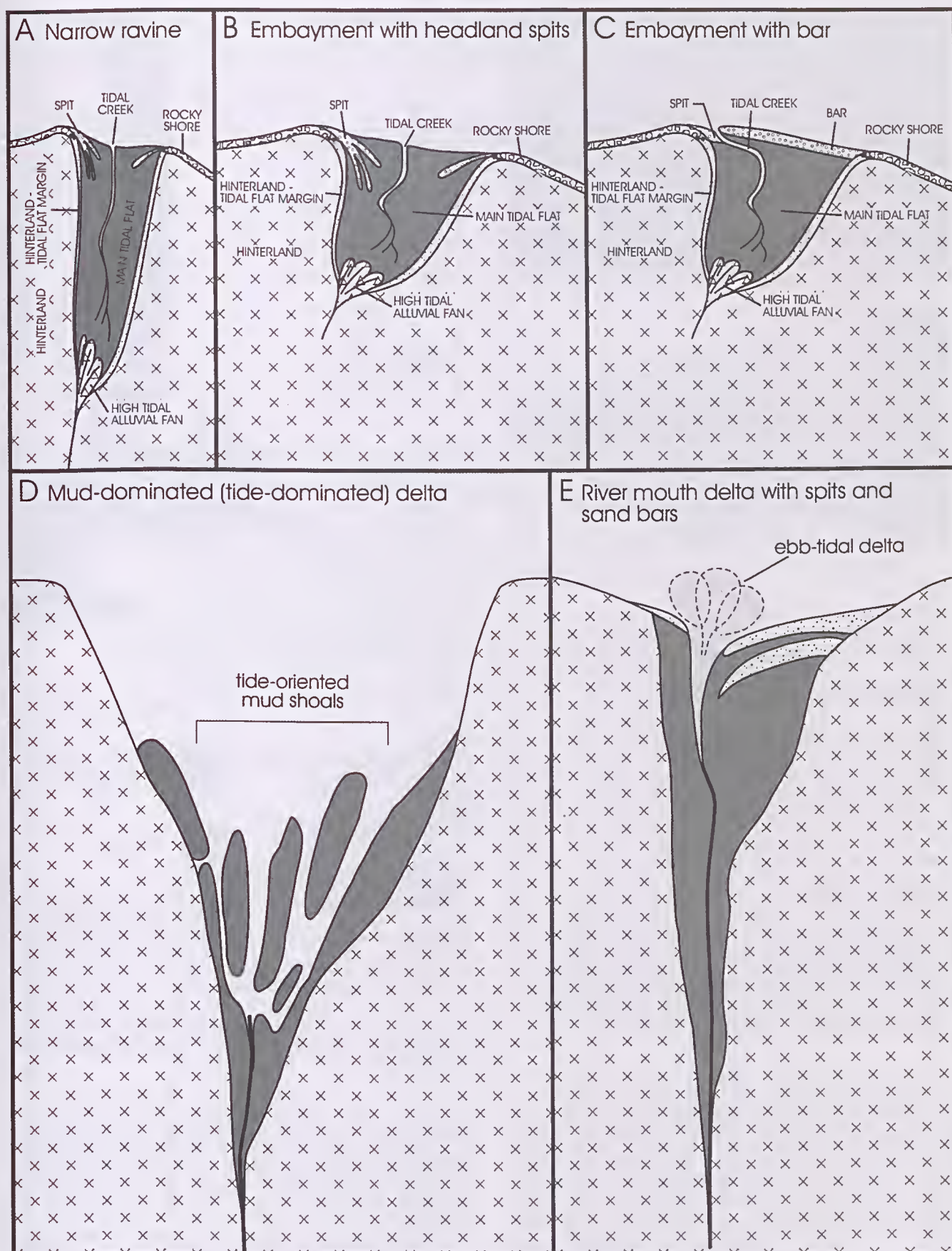


Figure 7. Key coastal settings for the assemblages of habitats along the Kimberley Coast. A. Narrow ravines. B. Open embayment with spits. C. Embayment with barrier bar. D. River mouth mud-dominated delta. E. River mouth delta with spits and sand bars; mangrove habitats include tidal flats, tidal creeks, hinterland margin, high-tidal alluvial fans, dune margins, and rocky shores.

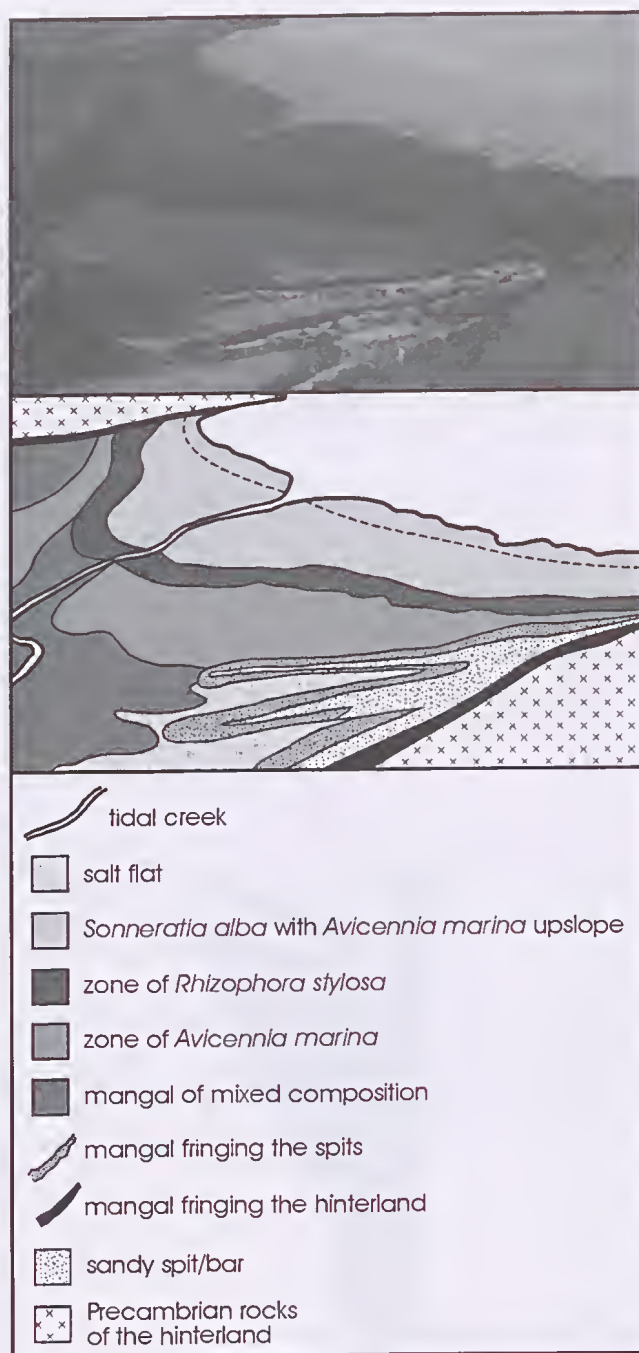


Figure 8. Mangrove habitats in a ria coastal setting: an embayment with tidal flat, tidal creek, spits, and hinterland margin. The mangal across the tidal flat is clearly zoned.

number of habitats, often there is a preferred habitat for a species or an association of species, and each habitat is suitable for only a limited range of species. The high-tidal alluvial fan, tidally inundated infrequently, with fresh water seepage illustrates this. With low seepage rates, it is the habitat of *Avicennia marina*, *Excoecaria agallocha* and *Lumnitzera racemosa*; with high seepage rates, it is the habitat of *Avicennia marina*, *Xylocarpus* sp, *Excoecaria agallocha* and *Lumnitzera racemosa*, and can also support *Bruguiera exaristata*, *Bruguiera parviflora*, and *Ceriops tagal*. The seaward edge of mangal inhabiting muddy tidal flats is the habitat of *Avicennia marina* and/or *Sonneratia alba*. Table 4 presents for each mangrove

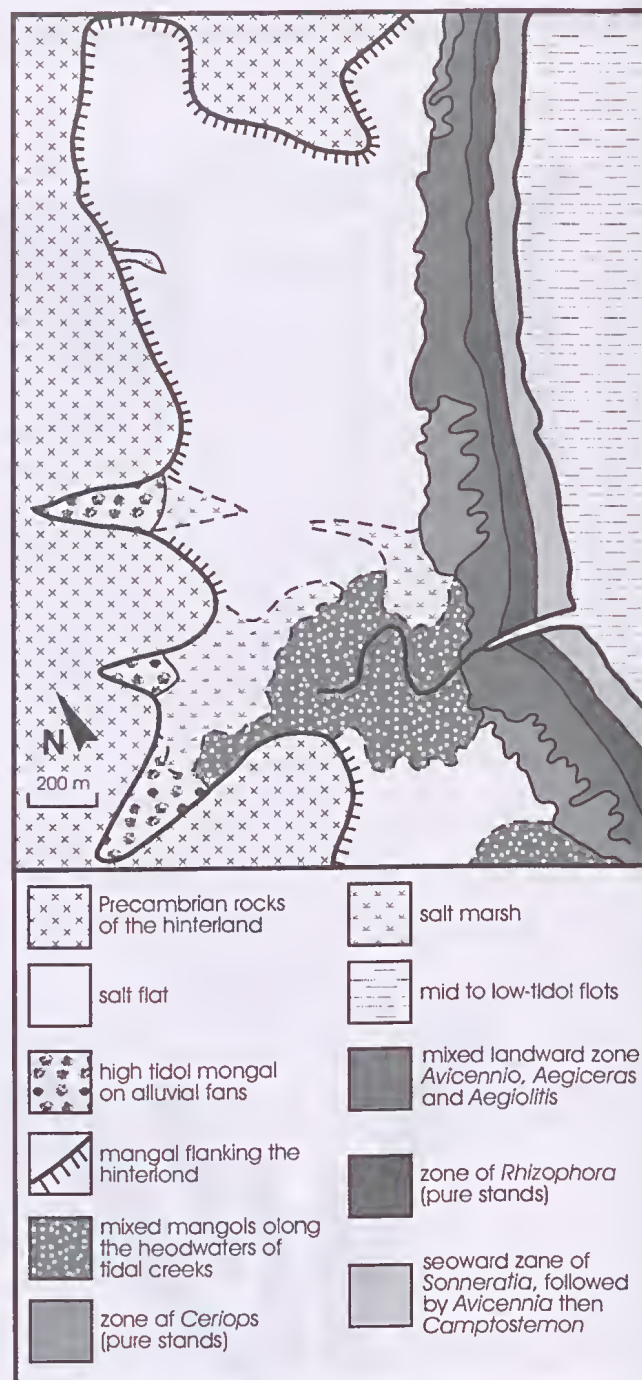


Figure 9. Embayment along ria coast in the Port Warrender area showing the mangrove habitats and species (modified from Semeniuk 1983).

habitat along the Kimberley Coast the species that occur (i.e., supported by that habitat). Some typical mangrove formations, in terms of their assemblage composition, structure, and physiognomy, in various habitats along the Kimberley Coast are shown in Figure 13.

Table 4 presents a generalised description of species that occur with the habitats along the Kimberley Coast, but because of local climate factors or because of more pronounced freshwater seepage (due to hinterland drainage), there is subregional variation in mangrove assemblages within habitats. The key habitats that

Table 4

Mangrove species and species associations inhabiting the various habitats along the Kimberley Coast

Habitat	Species and species associations
Tidal flat (muddy tidal flats)	zoned mangroves, with seaward <i>Avicennia marina</i> and/or <i>Sonneratia alba</i> , followed to landward by <i>Rhizophora stylosa</i> , then <i>Bruguiera exaristata</i> (and <i>Bruguiera parviflora</i>), <i>Ceriops tagal</i> and to landward <i>Avicennia marina</i>
Rocky/bouldery shore	zoned mangroves, with seaward <i>Avicennia marina</i> followed to landward by <i>Rhizophora stylosa</i> , then <i>Ceriops tagal</i> and <i>Avicennia marina</i>
Tidal creek bank	zoned mangroves, with seaward <i>Avicennia marina</i> and/or <i>Camptostemon schultzei</i> , with <i>Aegialitis annulata</i> and <i>Aegiceras corniculatum</i> , followed to landward by <i>Rhizophora stylosa</i>
Tidal creek point bar	zoned mangroves, with <i>Avicennia marina</i> and/or <i>Aegialitis annulata</i> and <i>Aegiceras corniculatum</i> , followed upslope by <i>Rhizophora stylosa</i>
Tidal creek shoal	zoned mangroves, with <i>Avicennia marina</i> and/or <i>Aegialitis annulata</i> and <i>Aegiceras corniculatum</i> Hinterland margin zoned mangroves, with <i>Avicennia marina</i> , <i>Aegialitis annulata</i> , <i>Ceriops tagal</i> , <i>Excoecaria agallocha</i> , <i>Lumnitzera racemosa</i> , and locally scattered <i>Xylocarpus moluccensis</i> ; in more northern warmer environments, rare <i>Scyphiphora hydrophyllacea</i>
High-tidal alluvial fan	with low freshwater seepage, zoned mangroves, with <i>Avicennia marina</i> , <i>Excoecaria agallocha</i> , and <i>Lumnitzera racemosa</i> , and rare <i>Ceriops tagal</i> ; with marked freshwater seepage, zoned mangroves, with <i>Avicennia marina</i> , <i>Bruguiera exaristata</i> , <i>Bruguiera parviflora</i> , <i>Ceriops tagal</i> , <i>Excoecaria agallocha</i> , and <i>Lumnitzera racemosa</i> , and locally scattered <i>Xylocarpus moluccensis</i> ; in more humid environments, locally scattered <i>Xylocarpus granatum</i>
Beaches	zoned mangroves, with seaward <i>Avicennia marina</i> (and sometimes <i>Sonneratia alba</i>) followed to landward by <i>Rhizophora stylosa</i> , then <i>Bruguiera exaristata</i> , <i>Ceriops tagal</i> and to landward <i>Avicennia marina</i> ; this habitat also supports <i>Aegialitis annulata</i> , and (especially where underlain by beach rock) <i>Osbornia octodonta</i>
Spits	zoned mangroves, with seaward <i>Avicennia marina</i> (and sometimes <i>Sonneratia alba</i>) followed to landward by <i>Rhizophora stylosa</i> , then <i>Bruguiera exaristata</i> , <i>Ceriops tagal</i> and to landward <i>Avicennia marina</i> ; spits in drier subregions are fringed by <i>Avicennia marina</i> and/or <i>Ceriops tagal</i> and/or <i>Excoecaria agallocha</i> and <i>Lumnitzera racemosa</i>
Cheniers	a fringe of <i>Avicennia marina</i> and/or <i>Ceriops tagal</i> ; in drier subregions are fringed by <i>Avicennia marina</i> and/or <i>Ceriops tagal</i> and/or <i>Excoecaria agallocha</i> and <i>Lumnitzera racemosa</i>
Barriers	zoned mangroves, with seaward <i>Avicennia marina</i> (and sometimes <i>Sonneratia alba</i>) followed to landward by <i>Rhizophora stylosa</i> , then <i>Bruguiera exaristata</i> , <i>Ceriops tagal</i> and to landward <i>Avicennia marina</i>
Dune margin	a fringe of <i>Avicennia marina</i> and/or <i>Ceriops tagal</i> ; in drier subregions are fringed by <i>Avicennia marina</i> and/or <i>Ceriops tagal</i> and/or <i>Excoecaria agallocha</i> and <i>Lumnitzera racemosa</i>

express variation in mangal composition, structure, and physiognomy across a climate gradient are: the hinterland margin where freshwater seepage is expressed; the high tidal alluvial fans where freshwater seepage is best expressed; beaches where freshwater is stored under the upper beach; spits and cheniers where freshwater is stored under the sand body; and the high-tidal parts of muddy tidal flats that are subject to evaporation and (in more arid areas) develop into salt flats.

The reason for the variation in mangal composition, structure, and physiognomy is that not all habitats respond equally to climatic or hinterland-physiographic setting because of their location along the tidal gradient and their proximity to hinterland terrestrial influences. It is possible to separate mangrove systems into dominantly marine-influenced and dominantly terrestrial-influenced zones (Figure 10 provides an idealised picture of decreasing marine influence across a tidal flat). Following Semeniuk (1983), these zones are:

1. from MSL to Mean High Water Neap Tide (MHWN), a zone dominated by marine influences; being inundated daily by tides; while air temperatures and sea

temperatures play a part in determining regional species distribution sub-continently, there is not enough differentiation in these climate parameters in the Kimberley region to markedly affect species composition in this zone, hence the species such as *Avicennia marina*, *Sonneratia alba*, *Rhizophora stylosa*, *Bruguiera exaristata*, and *Aegialitis annulata* are generally widespread and cosmopolitan in this tidal interval, particularly on muddy tidal flats;

2. from MHWN to HAT, a zone progressively dominated more by terrestrial influences, with terrestrial effects increasing from Mean High Water Spring (MHWS) to HAT; being inundated less frequently by tides and affected by evaporation (through solar radiation, air temperatures and wind), and rainfall (expressed as rain directly falling on saline high tidal flats, run-off, freshwater seepage, and base-flow of creeks, streams and rivulets); in these environments, changes in rainfall, and the extent the hinterland can deliver freshwater to the high-tidal zone through creeks, streams and rivulets or through freshwater seepage, determine species composition, structure and physiognomy; there are specific species associations, and

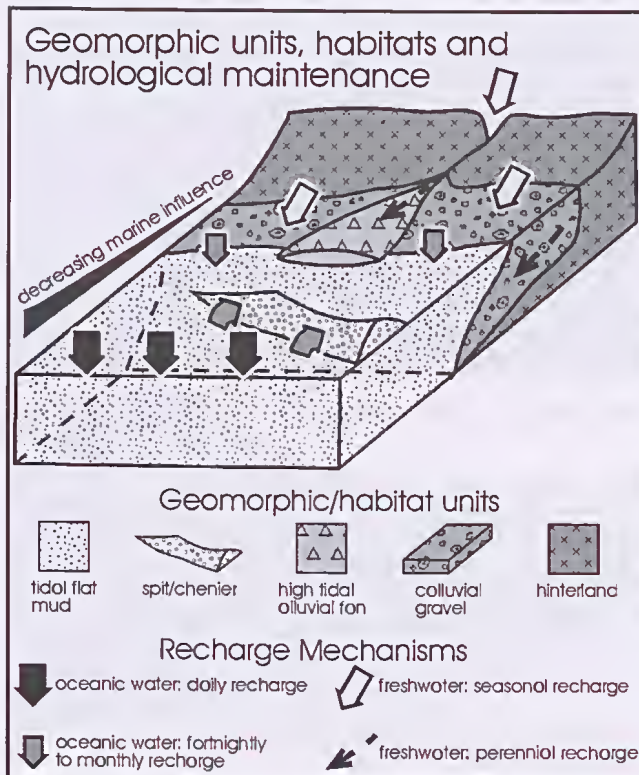


Figure 10. Suite of habitats with diverse substrate types within a ria coast embayment, and the various hydrological/hydrochemical mechanisms maintaining the mangroves. From MSL to the edge of the tidal flat along the edge of the hinterland, there is a decreasing marine influence.

expressions of mangrove structure and physiognomy in relation to substrate, tidal zone aquifers (e.g., emergent cheniers) or terrestrial aquifers that store and deliver freshwater (e.g., dunes bordering beaches, or fractured rock hinterland, or valley-tract alluvial ribbons), as well as the style by which freshwater is delivered to the high-tidal zone, and tidal level.

The freshwater input into the marine environment occurs through river/creek discharge after rainfall as well

as sheet flooding during the frequent high rainfall events, and subterranean groundwater seepage into the coastal zone is important during the wet and dry seasons. Semeniuk (1983) documents the regional climatic differences in north-western Australia and the importance of subsurface seepage in the north-west of Australia and postulates its importance for mangrove distribution. Bridgewater & Cresswell (2003) note differences in mangal phytogeography between the east and west coasts of Australia suggesting the more restricted western Australian groupings are determined by the amount of groundwater flow, which enables only the highly halophytic mangrove species to persist. The effect of rainfall on the habitat, and mangrove species occurrences in the critical freshwater-influenced habitats is presented in Table 5 below. There are also changes in vegetation structure, physiognomy, and density changes within the habitat with increased rainfall, but we focus here only on floristic changes.

A model to explain mangrove distribution and diversity along the Kimberley Coast

The mangrove habitats of the Kimberley Coast draw their species from the regional species pool. While there is some variation in species richness across the region (such as the loss of *Scyphiphora hydrophyllacea* and *Xylocarpus granatum*) the Kimberley Coast can be broadly considered to be one pool of 15 core species. Subregionally local factors determine those species that will inhabit the twelve mangrove habitats in the region (Table 2) to form mangal with variable composition and variable structure and physiognomy. The 'selection' of species from the regional species pool (and the variable expression of these species by habitat factors) creates the mosaics of species assemblages evident along the coast within the twelve habitats described above. The distribution of the main mangrove species within each of these twelve habitats is then further determined by regional climate and local freshwater input. Figure 14 summarises the main patterns determining distribution and diversity. It illustrates the progressive forcing factors in decreasing scale acting on the global species pool

Table 5

Effect of increased rainfall or increased seepage, or run-off on habitat and occurrences of species

Habitat	Effect of increased rainfall or increased seepage, or run-off
Hinterland margin	increased freshwater seepage from fracture rock aquifer; with increased seepage <i>Avicennia marina</i> and scattered <i>Ceriops tagal</i> changes to complex association of <i>Avicennia marina</i> , <i>Ceriops tagal</i> , <i>Lumnitzera racemosa</i> , <i>Bruguiera exaristata</i> , <i>Excoecaria agallocha</i> , and in the wettest areas <i>Xylocarpus granatum</i>
High tidal alluvial fan	increased freshwater run-off, alluvial base-flow, and seepage; with increased seepage <i>Avicennia marina</i> , <i>Lumnitzera racemosa</i> and scattered <i>Ceriops tagal</i> changes to complex association of <i>Avicennia marina</i> , <i>Ceriops tagal</i> , <i>Lumnitzera racemosa</i> , <i>Bruguiera exaristata</i> , <i>Excoecaria agallocha</i> , <i>Rhizophora stylosa</i> , and in the wettest areas <i>Xylocarpus granatum</i>
Beaches, spits, chenier	increased storage of freshwater in sandy aquifer landward of mangrove habitats, and increased seepage from aquifer; with increased seepage <i>Avicennia marina</i> , <i>Ceriops tagal</i> and <i>Bruguiera exaristata</i> changes to complex association of <i>Avicennia marina</i> , <i>Ceriops tagal</i> , <i>Bruguiera exaristata</i> , <i>Rhizophora stylosa</i> , and <i>Osbornia octodonta</i>
High-tidal muddy tidal flat	decreased evaporation of the salt flats, and increased freshwater dilution of saline flats; with increased rainfall, thickets of <i>Ceriops tagal</i> and salt flats change to forests of <i>Ceriops tagal</i> , <i>Bruguiera exaristata</i> , <i>Bruguiera parviflora</i> , <i>Osbornia octodonta</i> , and <i>Lumnitzera racemosa</i>



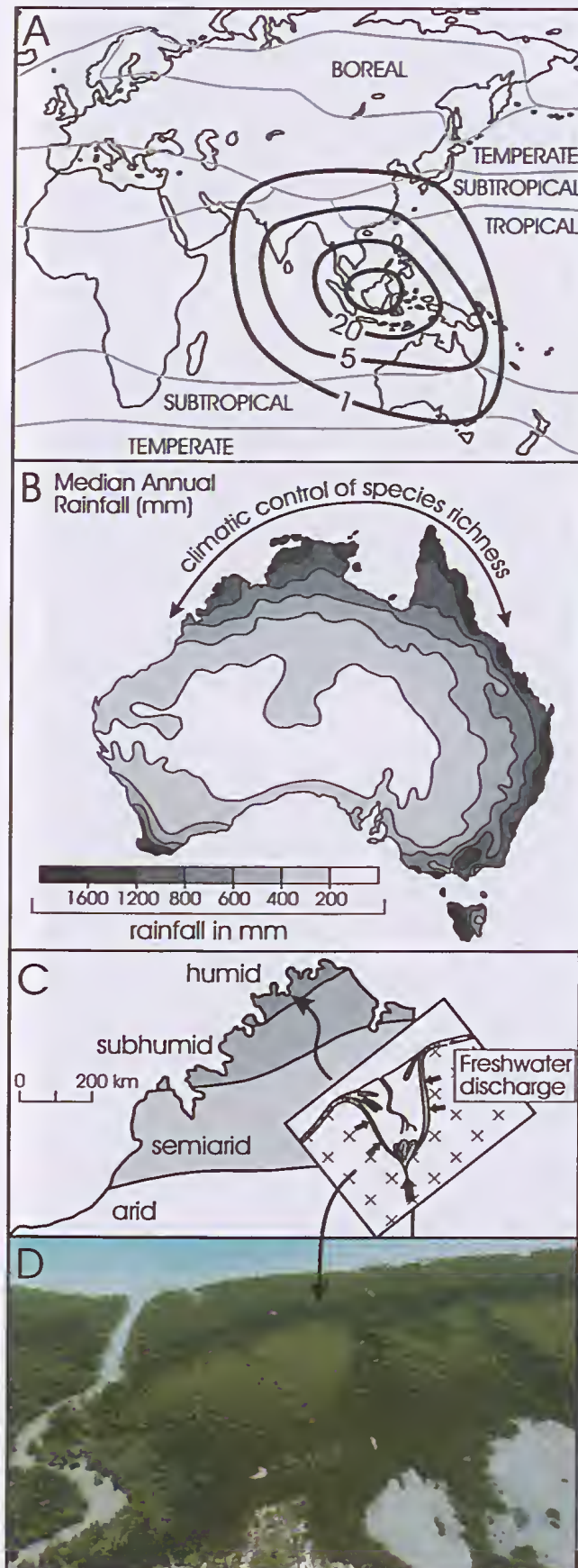
Figure 11. Aerial photographs of mangrove coastal settings and mangrove habitats. A. Large, narrow v-shaped gulf, and subsidiary fracture-controlled narrow ravines. B. Fracture-controlled narrow ravine barred by a sand barrier. C. Mangrove-lined branching, dendritic embayments (rias). D. Mangrove-lined branching small gulfs (rias). E. Network of dendritic drainage and associated landforms with mangrove vegetated muddy tidal flats in sheltered areas and in embayments, and sandy coves, beaches, and rocky shores on the wave-exposed open coast. F. Open embayment with spits at the headlands. G. Spits and tidal creek point bars at the front of a mangrove-vegetated delta, comprised of sand and mud, and tidally oriented shoals. H. Barrier of beach ridges barring a lagoon and embayment. I. Sandy spit complex protecting a mangrove-vegetated lagoon and embayment.



Figure 12. Oblique photographs of mangrove coastal settings and habitats. A. Rocky shore along the Buccaneer Archipelago with thin fringe of mangroves. B. Mangroves (zoned) inhabiting a low gradient gravelly shore. C. Mangroves inhabiting the tidal parts of (fracture-controlled) narrow ravines. D. Mangrove-vegetated tidal flat and meandering tidal creek (located inside a narrow, elongate v-shaped embayment). E. Gravelly spit partially protecting an open embayment, with zoned mangal within the embayment; chenier in the interior of the embayment is fringed by narrow mangal; mangrove-vegetated high-tidal alluvial fan is developed where a small ravine has debouched onto the high-tidal part of the salt flat. F. Narrow ravine, with sandy barrier across a mangrove-vegetated lagoon. G. Interface of rocky hinterland and salt flat, with mangroves fringing the hinterland margin and the alluvial fans. H. Mangroves inhabiting a sandy beach cove. I. Sandy spits and associated protected mangrove-vegetated lagoons. J. Broad muddy tidal flats with zoned mangroves along the seaward edge, and thin fringe of mangroves inhabiting the hinterland margin.



Figure 13. Features of the mangroves of the Kimberley Coast. A. Closed low forest of *Sonneratia alba* in the seaward front of the mangal. B. Closed low forest of *Rhizophora stylosa* of the mangal interior. C. Closed low forest of *Avicennia marina* of the mangal interior. D. Mangal inhabiting terraced rocky shore. E. Zoned mangal inhabiting a high-tidal alluvial fan, composed of an outer fringe of shrubs of *Avicennia marina*, and an interior tall forest of *Rhizophora stylosa*, *Bruguiera parviflora*, *Bruguiera exaristata*, and *Ceriops tagal*. F. Mangroves (*Ceriops tagal*, *Bruguiera exaristata*, and *Avicennia marina*) inhabiting the bouldery hinterland margin – boob trees and grasses to the right on the terrestrial slope; and G. Seaward margin of a high-tidal alluvial fan, with shrub of *Avicennia marina* and graminoid ground cover. H. Closed low forest of *Avicennia marina*, *Rhizophora stylosa*, *Bruguiera exaristata*, *Ceriops tagal*, and *Osbornia octodonta* along a sandy slope (beach) in front of a beach rock pavement.



leading to the species richness, assemblages, structure and physiognomy of mangroves along the Kimberley Coast. From a global species pool of Old World Mangroves in excess of 30 species centred on the Malaysian Archipelago, the progressive change in climate towards northern and north-western Australia results in a regional species pool of some 10–20 species across the Northern Territory and the Kimberley region. Smaller scale climate variation and local habitat characteristics along the Kimberley Coast further selects species from the regional pool to develop the habitat-specific assemblages and the climate-specific and habitat-specific species occurrence.

The main factors involved in determining species diversity at the fine mangrove habitat scale are: 1. oceanographic processes determining accumulation and maintenance of sediment bodies to develop as habitats; 2. the terrestrial sedimentary processes that determine accumulation and maintenance of sediment bodies, such as alluvial fans; 3. the marine hydrological and hydrochemical processes that determine accumulation and maintenance of mangrove habitats; and 4. the amount of freshwater delivered to the high-tidal zone. These factors result in the expression of species in distinct habitat-related assemblages, often zoned across the habitat in relationship to environmental gradients developed within the habitat (Fig. 14D). Variations also occur in relation to the dynamic nature of the coastal environments. Long-term stable habitats result in long-term assemblages and in stable mangal zonation. Dynamic environments, or those where there have been geomorphic or hydrologic adjustments will result in floristically and structurally less stable assemblages.

Some general patterns emerge:

1. The rocky shores are mangrove-depauperate.
2. The high-energy sandy shores also are mangrove-depauperate.
3. On moderate energy sandy shores, *e.g.*, beaches, spits, and cheniers which support mangroves, species composition is determined by grainsize, sediment composition, hydrological factors such as internal drainage and freshwater storage and seepage, hydrochemistry, and tidal level.

Figure 14. Diagram illustrating the progressive forcing factors, in decreasing scale, acting on the global species pool leading to the regional species pool along northern Australia and the Kimberley region then to the habitat-specific assemblages and the climate-specific and habitat-specific species occurrence. A. The species richness of the Old World mangroves (isopleths denote the general numbers of mangrove species). B. The mean annual rainfall across north-western, northern and eastern Australia that influences the species richness at the sub-continental scale. C. The climate of the Kimberley region that determines which species from the sub-continental species pool are available to generate a regional species pool, as well as the further selection of species by habitat factors (the generalised ria embayment shown here (inset) with array of habitats and with locations of freshwater seepage). D. Gradients within the habitats force species into zones of composition, structure and physiognomy; in this example, compositional and structural zonation of species is following tidal flat gradients, and the effects of shore-normal tidal creeks.

4. The muddy tidal flats where there is protection from high energy conditions are mangrove-rich zones, and if the environment is stable geomorphically and hydrologically/hydrochemically then the full complement of mangrove species are zoned according to gradients of environmental conditions.
5. In tidal creeks there is a subset of habitats which are relatively mangrove-rich; these subsets of habitats include steep creek banks, point bars, and mid channel shoals.
6. Where there is freshwater seepage, such as along the margin of the hinterland, and from high-tidal alluvial fans, the habitats, though generally mangrove-depauperate, increase in species richness with increased freshwater seepage.

The finest scale manifestation of diversity in mangroves is the physiognomic, structural and floral expression at the habitat level. Here, salinity, inter-species competition, intra-species competition, type of substrate and nutrients, and amount of hydrological through-flow, are the major factors that determine how individual species manifest various structural and physiognomic forms. For instance (reflecting habitat differences in terms of substrate, tidal level, and salinity), the structure and physiognomy of a *Ceriops tagal* low forest or a *Bruguiera exaristata* low forest on a muddy tidal flat will be structurally and physiognomically different to a *Ceriops tagal* thicket or a *Bruguiera exaristata* scrub fringing a sand spit and, similarly, a formation of scattered *Lumnitzera racemosa* as multi-stemmed shrubs along a high-tidal alluvial fan will be different to a single-trunked stand of *Lumnitzera racemosa* co-associated with *Avicennia marina* along a landward fringe adjoining a salt flat.

Thus, the environmental conditions of the habitat, and the resulting zoning of the habitat drive the different expressions of the structure and physiognomy of individual species which provide the finest scale expression of biodiversity in the region. These expressions represent physico-chemical differences in the environment which may also host significant variations in more cryptic fauna and micro-biota. Therefore to truly capture the physiognomic and structural expression in relation to mangrove flora, it is not sufficient to simply note which mangrove species are present. It is at this finer scale of mangrove expression that a more fulsome analysis of biodiversity must be explored.

Discussion

The Kimberley Coast occupies a unique position globally in terms of its tropical latitude, ria coast setting, and rainfall, within a mostly macrotidal regime, and the mangroves therein also acquire global significance.

The mangroves along the Kimberley Coast reside in a tropical humid to subhumid climate in the species-rich setting of the Old World Mangroves, and are located along a macrotidal ria shore, a setting that is unusual around the Globe. For instance, the areas of mangrove-species-rich Queensland, and the Malaysian Archipelago are not ria coasts and do not have the rich range of ria

coast settings wherein species can express themselves variably in different associations, and in different structural and physiognomic forms responding to habitat and hydrology/hydrochemistry. Globally ria coasts are not common (Brocx & Semeniuk 2011), and most are not mangrove coasts. Where mangroves and (small scale) ria coasts coincide on other continents, the mangroves are New World Mangroves. The Kimberley Coast uniquely carries the Old World Mangroves into a ria coastal environment.

The mangroves of the Kimberley region belong to the Indo-Malesian group of Old World Mangroves centred in the Indian-Pacific area (Tomlinson 1986, Chapman 1977), which is the most species-rich region of the world. Spalding *et al.* (1997) describe the overall global distribution of mangroves with the most species occurring in tropical climates, and a reduction in species in higher latitudes. Suzuki and Saenger (1996) in a comparison of mangrove vegetation at similar latitudes between eastern Australia and Japan note that the Australian mangrove flora is one of the richest in the world, and Duke *et al.* (1998) document the species diversity within the Indo-Malesian group also noting that the mangrove flora of the Australasian region is one of the richest in the world, with Australia recording 39 of the 58 taxa found in the 'Indo West Pacific' hemisphere. Duke (1992) relates latitudinal (temperature) and rainfall patterns to the number of mangrove species present, with a decrease in species from the tropical north southwards.

The Kimberley Coast is the largest laterally extensive ria coast in the World and, in this context, it presents a range of coastal forms variable in shape, size, and orientation but developed on a regionally relatively consistent bedrock template, *viz.*, the rocks of the Kimberley Basin and the seaward expression of the Kimberley Plateau. The ensemble of coasts along the Kimberley Basin and adjoining King Leopold Orogen present a global example of the range of fracture-and-fault controlled ria coasts that can be developed, and has been recognised as such in the preliminary assessment of the heritage values of the West Kimberley (Australian Heritage Council 2010). The mangrove habitats exhibit a recurring pattern across the length of the Kimberley region.

One of the important features of the region is the freshwater seepage and the freshwater storage in spits and cheniers. The fracture-dominated bedrock that forms the hinterland to the mangrove-lined coast provides a globally unique expression of the phenomenon of freshwater seepage into hinterland margin habitats and into high-tidal alluvial fans. The region is located in a climate that alternates between dry season and wet season, and the freshwater residing in a fractured bedrock (fractured aquifer) discharges into the tidal zone during the wet and into the dry season. This controls the occurrence and maintenance of mangroves in the high-tidal zone and is a feature unique globally and of international significance in mangrove ecology. Similarly, the spits and cheniers, in a monsoonal setting, provide specific hydrological and hydrochemical function to the mangroves. With freshwater discharge along the edges of the sand bodies into adjoining tidal flats, there are specific mangrove ecological processes operating within this ria coast setting.

The Kimberley Coast manifests a range of habitats for mangroves related to larger scale hinterland influences, coastal landforms, coastally expressed geological patterns, shoreline sedimentation patterns, and climate; varying from rocky (cliff) shores to classic ria shores with tidal flats, tidal creeks, spits, and high-tidal alluvial fans, to rocky-shore-dominated ravines, amongst others. The mangroves form habitat-specific assemblages and characteristic floristic and structural zones within the mangal. The complexity of mangrove habitats and their relationship to the megascale coastal forms of this regional coastal setting is of international conservation significance.

The approach adopted in this paper, involving scale of coastal setting for mangroves, identification of habitats, explanation of mangrove diversity (floristically, structurally and physiognomically) in relation to habitat, and the stratified scalar approach integrating global species richness to local species richness with climate gradients and habitats, is applicable elsewhere in Australia and globally. This approach provides a framework for studies at the next level of mangrove ecology involving transect work describing species zonation, abiotic factors underpinning the zonation, inter-species competition, species tolerance levels to physiochemical gradients, changes in plant physiognomy across habitats in relation to physicochemical gradients, and density between habitats.

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Holocene Growth History and Evolution of the Scott Reef Carbonate Platform and Coral Reef

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Abstract

As a prominent isolated oceanic atoll-like reef within the Oceanic Shoals Biozone to the west of the Kimberley coast, Scott Reef is a small carbonate platform located in a distal ramp setting on Australia's Northwest Shelf. Rising from depths of 400–700 m it is a complex of two large isolated coral reefs separated by a deep channel; the pear-shaped North Reef and the crescent-shaped South Reef. Small differences in subsidence rates indicate differential subsidence between the paired platforms. Holocene (MIS 1, last 10 ka) reef initiation was at 11.3 ka, soon after Meltwater Pulse 1B thereby bracketing the Holocene growth phase to the subsequent deglaciation sea-level rise. The crest of southeast North Reef (and the rising sea-level) reached close to present sea level (–1.5 m LAT) by 2.7 ka ago. There is no record of the southwest Australian sea level high stand of about +2 m some 7 ka BP. The Holocene reef growth history record obtained for this long lived and resilient reef system is one of the most detailed yet for the western margin of Australia.

Keywords: Scott Reef, Kimberley, North West Shelf, Oceanic Shoals Biozone, global sea levels, marine isotope stages, subsidence, carbonate platform, cores, growth history, coral reef

Introduction

Coral reefs have long proved attractive for studies by biologists and geologists, the former focusing on their biodiversity values and the latter interested in longer term reef evolution, with the knowledge that coral reefs have been important in earth history. Since the recognition of subsidence as a control on coral reef formation (Darwin 1842) and the realisation of the role of glacial sea level low stands in reef development of the Quaternary (last 2 million years) time (Daly 1910), coral reefs have been prominent in marine geological research. Kimberley coral reefs first received attention through the pioneering studies of Fairbridge (1950), but have remained poorly known geologically since that time with some recent exceptions. Montaggioni (2005) and Montaggioni & Braithwaite (2009) summarised the history of geological research on Indo-Pacific reefs and described the last three decades of subsurface investigations of reef growth since the last glaciation (last 23 ka), recognizing four basic patterns of reef anatomy. Studies of Australian reefs have been dominated by work on the eastern seaboard and the Great Barrier Reef (see Hopley *et al.* 2007), but reefs of the western continental margin of Australia (with the exception of the Houtman Abrolhos and Ningaloo Reefs; Collins 2010) and its bordering Cretaceous-Tertiary carbonate ramps remain relatively poorly known. Coral reefs of Australia's western margin (Fig. 1) include isolated oceanic atoll-like reefs (Ashmore Reef, Seringapatam and Scott Reefs,

Rowley Shoals); island-associated shelf reefs and fringing reefs of the Kimberley coast and Dampier Archipelago; Pilbara reefs (Barrow and Montebello Islands); Ningaloo Reef, a fringing reef adjacent to the North West Cape, and the outer shelf Houtman Abrolhos carbonate platforms and reefs, the southernmost coral reefs in the Indian Ocean.

This paper provides new insights into the growth history of Scott Reef (Fig. 1), one of the most prominent isolated oceanic atoll-like reefs within the Oceanic Shoals Biozone to the west of the Kimberley coast. As an isolated carbonate platform and coral reef Scott Reef is located in a distal ramp setting on Australia's Northwest Shelf (Collins 2002, 2010; this volume). Scott Reef rises from depths of 400–700 m and is a complex of two large isolated coral reefs separated by a deep channel; North Reef and South Reef (Berry & Marsh 1986).

Methods

Two generations of shallow seismic data were relevant to the study; the 2000 Curtin seismic survey, a shallow boomer survey conducted using RV *Franklin* and small vessels, which included reef margin and lagoon lines, and sampled surface sediments, and the shallow site test cores in reef and lagoon environments taken by Woodside Energy Ltd (WEL) in 2006/7 and these became available in 2008/9 for a study of reef architecture and growth history. Core logging and sampling were carried out to identify the major events and stages in reef development by recording sediment/rock types, primary, secondary and associated reef builders, coral

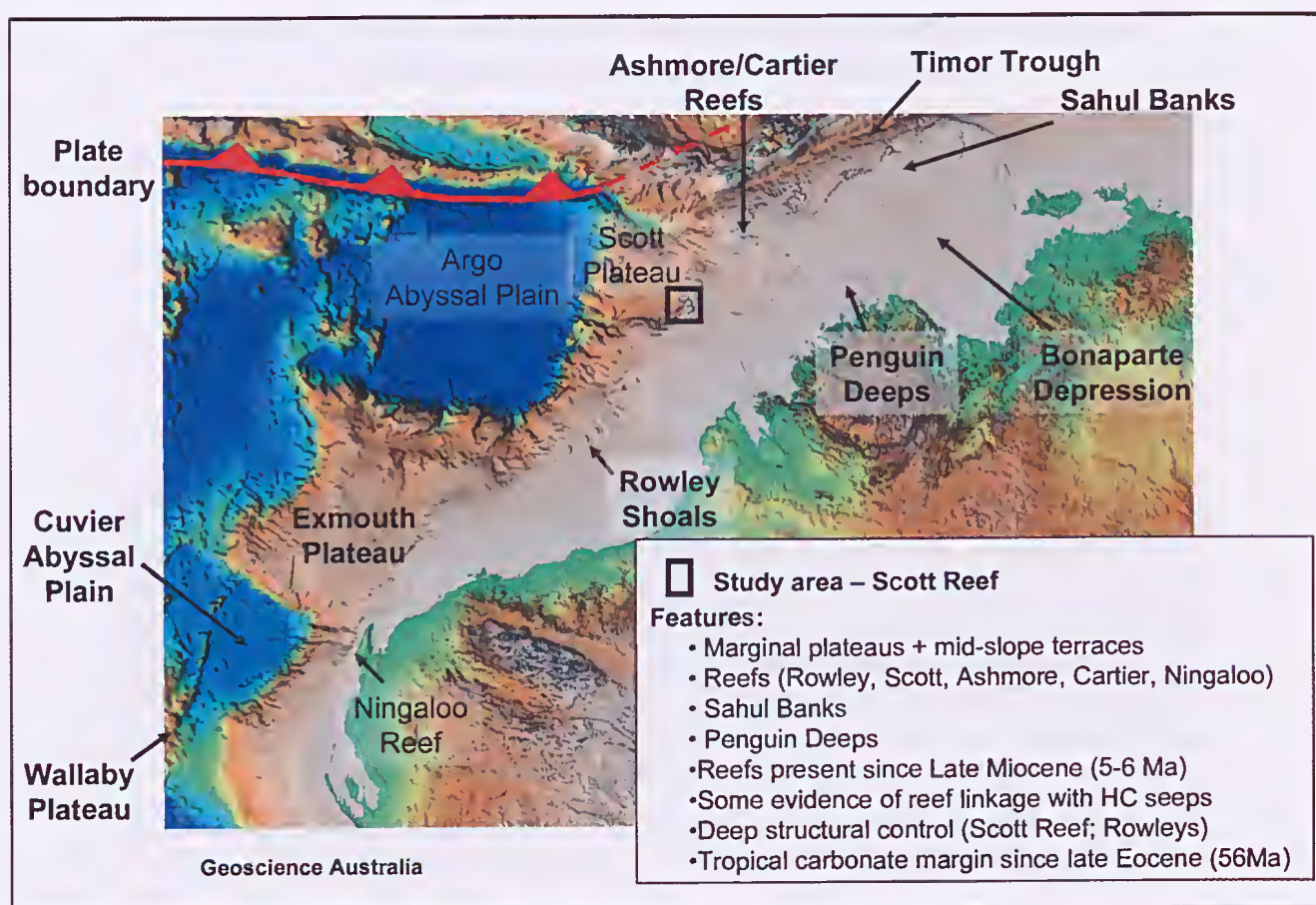


Figure 1. Regional setting of Scott Reef and northwest margin of Australia (after Geoscience Australia).

communities and morphologies, and hiatuses in reef growth. Cores were then correlated to interpreted seismic sections and significant seismic reflectors mapped. Selected sections were used for detailed microscopic study to better characterise the main rock types (lithologies), patterns of cementation, diagenetic changes, and porosity development. Of the logged cores a selection from the data base was made for the purposes of this paper.

Core/rock types were classified following the Expanded Dunham Classification (Embry & Clovan 1971) for depositional textures. For each rock facies (type) the related reef community was documented. Grain size classification followed Udden-Wentworth (1922). The full analysis of the reef framework itself followed the terminology suggested by Montaggioni (2005) which highlights the dominant coral growth forms, their role as reef builders and environment indicators. Additional terminology was introduced in order to manage the variability of the dataset presented in this work.

Least altered coral samples were selected for high-precision U-series dating using a VG Sector-54 Thermal Ionisation Mass Spectrometer (TIMS) at the University of Queensland (UQ) following the procedures described in Zhao *et al.* (2001) and Yu *et al.* (2006). ^{230}Th ages were calculated using Isoplot/Ex 3.0 Program of Ludwig (2003).

Setting and Oceanography

Scott Reef is under the influence of the Indonesian Throughflow, which modulates the exchange of waters and heat between the Pacific and Eastern Indian Ocean, and flows east-west through Scott Reef (Pandey *et al.* 2007). It is a high hydrodynamic environment. Tidal currents seem to be dominant in influencing the sediment transport rather than oceanic swell (Harris *et al.* 1991).

The formation of internal waves was shown by Wolanski & Delleersnijder (1998) to be an interaction between tidal currents (tidal range of 4m, classified as high mesotidal *sensu* Hayes 1975) and overall morphology of Scott Reef. The proposed model suggests a counterclockwise rotation of the wave around the island, reaching with maximum amplitude along the island slopes, peak velocities of 0.7m/s, and showing an absence of eddies in the lee of the island. The hydrodynamic energy generated is partially transferred to the open ocean (Wolanski & Delleersnijder 1998). The possibility of flow separation due to the overall morphology may explain differences in reef development, although this was not depicted in their model. Importantly, the model suggests waves of 60 m peak to trough, which would promote major influences on the current patterns and distribution of temperature and salinity in the top 200 m of the water column. Wolanski & Delesalle (1995) suggested the potential of

these waves bringing nutrients from below the pycnocline (located at 100 m depth) to within 40 m of the surface where other small-scale flow processes would occur. This would therefore promote reef development near the surface. Brinkman *et al.* (2008) have demonstrated that the Scott Reef environment is strongly thermally stratified and also demonstrated how the hydrodynamics can play an important role in larval dispersion and bleaching events. Scott Reef has semi-diurnal tides with a tidal range of 4.1m (National Tidal Centre 2009a, b; meso-high tidal range, *sensu* Hayes 1975). The region lies in the monsoonal belt with prevailing westerly or northwesterly rain-bearing winds from November–March, and dry southeasterly or easterly trade winds from May to September. The region is cyclone-influenced (average 3 per year, Lough 1998) and has southwest prevailing swell. The environmental importance of Scott Reef lies partly in the potential record it contains of the biological exchange between two oceans since its establishment in the Late Tertiary.

Regional Geology and Geomorphology

Scott Reef (Fig. 1) is a complex of two large isolated coral reefs developed on top of an anticlinal structure of Triassic age, faulted down to the northwest on the northwest side by Late Triassic movement (BOC 1971 a, b; BOC 1972). A Carnian to Norian age for onset of inversion and initiation of the Scott Reef high is based on biostratigraphy (Struckmeyer *et al.* 1998) (Fig. 3.) The Scott Plateau and its northeastern extension delineate the western limit of the Browse Basin. Seismic data suggest that the plateau consists of uplifted, relatively shallow Palaeozoic and Precambrian rocks overlain by thin (<1000 m) Cretaceous and younger sediments (Stephenson & Cadman 1994; Symonds *et al.* 1994). Throughout the Permian and Jurassic, the Scott Plateau was probably

above mean sea level, providing a source of clastic sediments for the Browse Basin (Stagg 1978). The Browse Basin developed in the Carboniferous to Early Permian as a result of north-northwest extension, which led to continental breakup in the Early Permian (Struckmeyer *et al.* 1998). Upper crustal faulting resulted in half-graben morphology and compartmentalisation into distinct depocentres. Resultant structures influenced the subsequent features, and near the end of the Triassic a major compressional event (defined by a regional unconformity) resulted in the generation of a series of large anticlines and synclines, including the Scott Reef and Brecknock trends (Struckmeyer *et al.* 1998). Post-breakup transgressive marine shales and claystones covered the Scott Reef trend by the Late Tithonian, and claystones, siltstones and marls dominate the Cretaceous section.

A section of Paleocene-Quaternary carbonates, 3,515m thick (mainly calcarenite, calcilutite and marl, with minor chert) underlies the Scott Reef platform (BOC 1971a, b; BOC 1972). The top 1,700 m consists of an undated reef complex which is dolomitised. A Middle Miocene to Burdigalian age was obtained within calcarenite, calcilutite and dolomite sections between 1,700–2,198m. Aquitanian calcarenite and marl sections at 2,198–2,379m unconformably overlie the Oligocene and Upper Eocene calcarenites, which continue down to 2,458m. Eocene and Upper Paleocene fine-grained carbonates and cherts continue from 2,458–3,484m. The remainder of the Upper Paleocene (claystones and marls) continues to 3,578m, and the Middle Paleocene rests unconformably on the Upper Cretaceous. The regional geological structure and the overlying carbonate sequence are shown in cross-section in Figure 2. The focus of this study has been to document the uppermost 30–40 m of cored reef section, the age of which ranges from present to some 10,000 years ago (Holocene; Marine Isotope Stage 1).

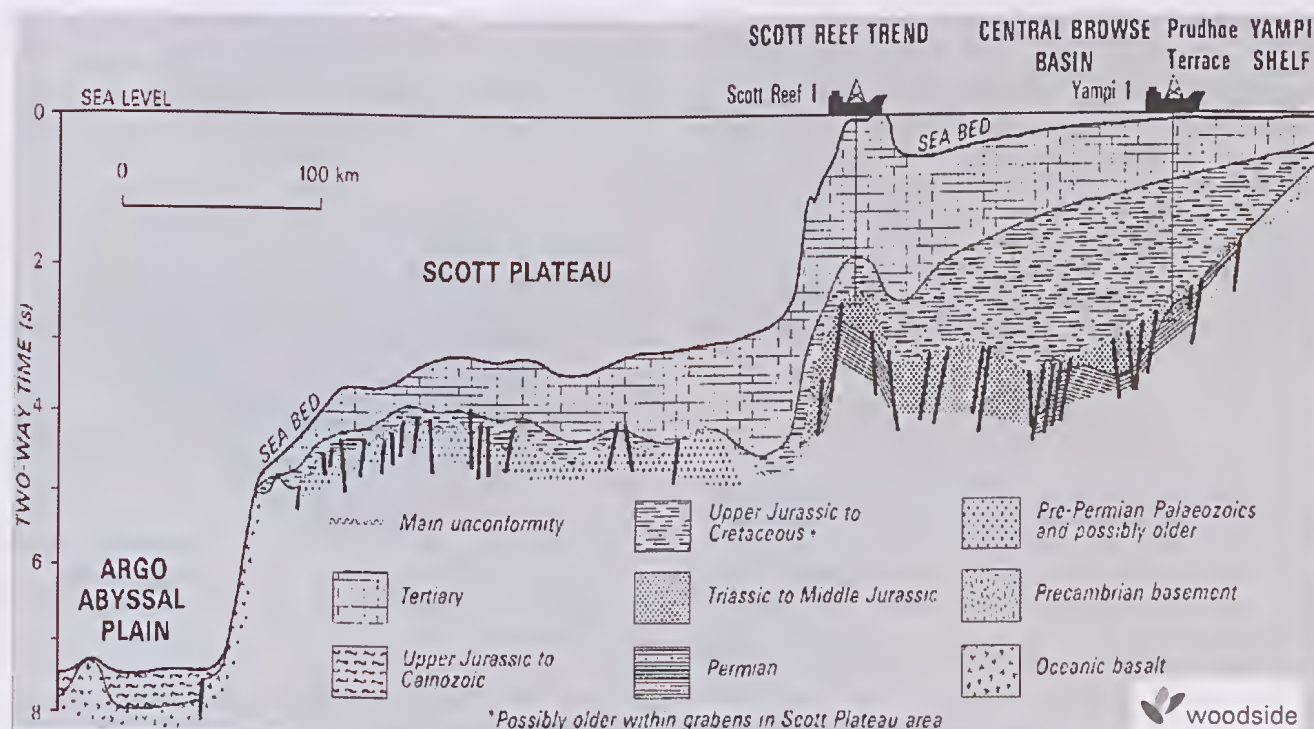


Figure 2. Schematic cross section of Central Browse Basin (from Woodside Energy Ltd). Note the position of Scott Reef, Scott Plateau and underlying geological structure. The Tertiary section consists of shelf and reef limestones.

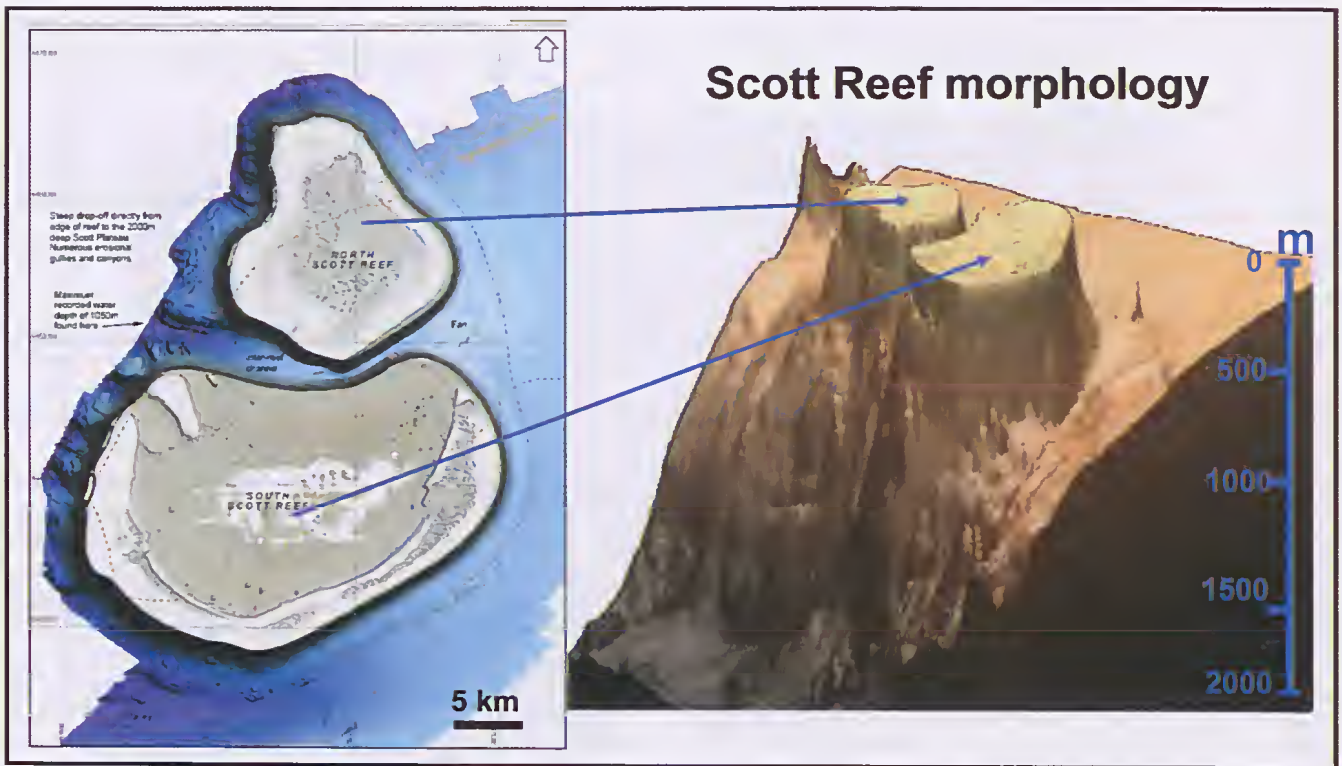


Figure 3. Scott Reef morphology, plan view and relief model. Note that Scott Reef rises from the continental shelf edge, enhancing the steepness of the slope. Talus deposits accumulate by downslope movement at the reef margin, whilst lagoon areas are scoured and reworked by strong hydrodynamic energy, generating mobile bedforms. (From Woodside Energy Ltd).

The geomorphology and digital elevation models of Scott Reef illustrate its proximity to the boundary of the Australian and Eurasian Plates, with marginal plateaux, mid-slope terraces and ocean deeps as shown in Figures 1 and 3. Scott Reef and related reef systems, such as Seringapatam to the north and the Rowley Shoals to the south, form a discontinuous reef rim which marks the position of a submerged, former continental margin, of probable Miocene (several millions of years) age. The North West Shelf is a carbonate ramp and the Scott Plateau forms part of its seaward margin (Fig. 3). Coral reef systems at the outer margin of the ramp such as the Rowley Shoals and Scott Reef were initiated and developed along (and mark the position of) an old continental margin formed some 5–6 million years ago (Late Miocene time) and have continued to grow through cycles of subsidence and sea level change throughout that time (Fig. 3).

Surficial Environments

Scott Reef rises from depths of 400–800 m on the distal portion of a carbonate ramp, and is similar in setting to 'downslope buildups' (*sensu* Read, 1985). It is a complex of two large isolated coral reefs separated by a deep channel; the pear-shaped North Reef and the crescent-shaped South Reef (Figs 3 and 4; Berry & Marsh, 1986). North Scott Reef is continuous except for two narrow passages, one in the southwest, and one in the northeast, with similar reef flat dimensions throughout. The outer reef flat is a mixture of scattered large boulders and occasional living corals. The outer reef gives way on its

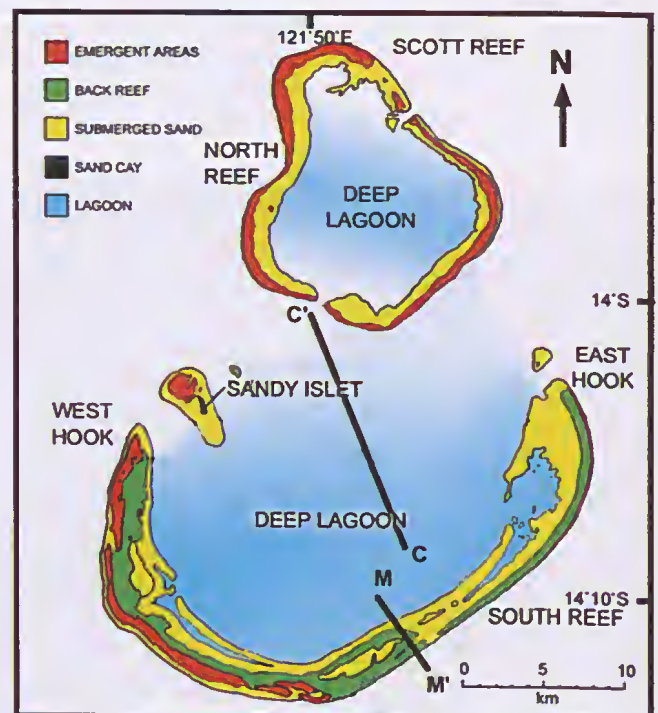


Figure 4. Scott Reef surface environments and position of selected shallow seismic lines showing lagoon and reef crest architecture.

seaward margin to a gentle slope followed by an irregular outer slope with surge channels extending to 30 m and steep gradient to seaward. The inner reef has low coral cover, some algal turf, and lacks a distinct boulder

zone. The back reef is deeper, with a more diverse coral fauna, and the lagoon is sandy with scattered corals (Done *et al.* 1994).

South Reef is open to the north, and is 27 km wide (east-west) and 20 km from north to south. The distance between the reefs is 5 km and the intervening channel is 400–700 m deep. The reef flat of the western part of South Scott Reef is over 2 km wide, and 600 m of reef flat is emergent at low water. Sandy Islet is a small, unvegetated sand cay situated atop a detached northwesterly portion of the reef. The eastern part of the reef is similar in morphology to the west reef, also with a detached sand cay, which is the only portion emergent at low water. The outer reef generally has encrusting coralline red algae and minor corals, and the reef flat includes boulder rubble, sand flats, algal turf and minor amounts of coral. The back reef is sandy with scattered large *Porites* colonies, other corals and sparse seagrass. Lagoon depths inside South Scott Reef are 35–55 m (*ca.* 30 m in North Reef) and there are isolated coral knolls, sandy areas, and hard substrates with sponges and stunted coral communities (Done *et al.* 1994).

Only very limited portions of the reef crest of both reefs are exposed during low tide, leaving the majority of the reef structure submerged and prone to colonization by reef-related communities. Both reef crests and lagoons have prolific development of coral patch reefs and other reef communities in association with large amounts of reworked boulders to gravel size reef fragments, reworked by episodic cyclonic storms (Gilmour & Smith 2006) and the general high hydrodynamic energy of strong metre tides and swells.

Coral assemblages identified by Done *et al.* (1994) are: Staghorn *Acropora* thickets, with moderate diversity of massive and branching corals (deep inner reef flats), *Goniastrea retiformis*/*Porites* massive community (sheltered reef flats and lagoon slopes), *Acropora brueggemannii* thickets (areas with moderate water motion), faviid, pocilloporid and *Acropora palifera* assemblage (areas with moderate-strong water motion), and the ‘Staghorn plus’ assemblage (lagoon floors). For more recent data see discussions of the reef by Smith *et al.* (2008).

Seismic Architecture

The overall seismic architecture is a flat-topped platform bounded by platform margin reefs which flank steep marginal slopes, as reflected in the current day surface environments. There are distinct cycles of upward platform growth which resemble “stacked saucers” in shape, each mimicking the previous cycle. Cycle boundaries are marked by platform-wide seismic discontinuities (R1, R2, and R3) which rise under marginal reef crests before falling steeply at the platform margins (Fig. 5).

Lagoon seismic structure and morphology: The deepest two reflectors identified on lagoon profiles are at 64m and 68m below SL (R2 and R3) respectively (see Fig. 5A), and are also identified in the cores investigated. These surfaces mark the tops of Marine Isotope Stages 7 and 9 and are sub-parallel to and lie below the prominent R1 reflector which is present throughout the lagoon at 50–55 mbsl. This surface is flat to hummocky,

and rises at the lagoon margins by as much as 10 m, towards the contemporary reef crests. There are two probable karst depressions in the reflector which are *ca.* 10 m deep (rim elevation: 50–53 m; floor 64 m) and up to 1.3 km across, steep sided and flat floored, with a younger reefal infill whose elevation lies distinctly below that of contemporary lagoon-floor pinnacle reefs. The reflector R1 is known to be the last interglacial surface (Marine Isotope Stage 5e, or MIS 5e) based on its apparent karstification and relatively uniform elevation as the substrate to Holocene accretion in the lagoon. It is consistently overlain by 10 m of Holocene reef and intervening hard substrate, the upper surface of which is the contemporary lagoon floor, composed of pinnacle reefs of 4–8 m elevation above a more flat, intervening substrate. Benthic sampling and seafloor video recordings show that the lagoon floor is a sediment-starved, mostly bedrock surface with a modern reefal community composed of encrusting coralline algae, corals and sponges, also with large boulders distributed apparently preferentially in the eastern side of the lagoon. There is a strong correlation between the growth positions of Holocene lagoon reefs and antecedent topography, in that most reef initiation took place upon highs in the last interglacial surface. In addition, reefs growing from the floors of karst depressions fill the depressions but grow to a level significantly below that of other lagoon reefs, whilst reefs on the depression rims rise above those of the general lagoon level (Fig. 6).

South Reef margin structure and morphology: Profiles of the arcuate, single- to double- crested reef, which rims the lagoon, show that the last interglacial reflector rises beneath reef crests and falls beneath inter-crest depressions, exerting an antecedent influence on younger (Holocene) reef growth (Fig. 5B). At the landward extremity of the platform margin reefs, the last interglacial surface has risen to 36 m below SL from the lagoon level of 60 m. A further rise to *ca.* 30 m below SL occurs beneath the Holocene crest (Fig. 5B; see profile M-M') before the reflector falls towards the seaward face of the Holocene reefs. Though the reflector is difficult to trace in its entirety to a seaward-sloping termination at the platform margin, it is clear that the last interglacial “rim” is a relatively low relief feature, reflecting lowstand erosional modification and/or subsequent beveling of a pre-existing reef crest during transgressive drowning. Core data and geochronology confirm the seismic results.

Reef Architecture, Frame Builders, Holocene, Sea Levels and Cycles

Core analysis together with seismic data and geochronology provided the opportunity to determine the nature of reef-building cycles and the dominant reef communities in different settings, the time frame of reef development, sea level history and coral reef growth response, and the overall architecture of reef development. Core transects were studied from the South Reef southeast margin and North Reef southeast margin, with isolated Cores at ancillary locations recording the Holocene reef growth cycle (MIS 1, representing the last 10,000 years, or Holocene time). These are usually *ca.* 30 m thick reef growth events and are discussed below.

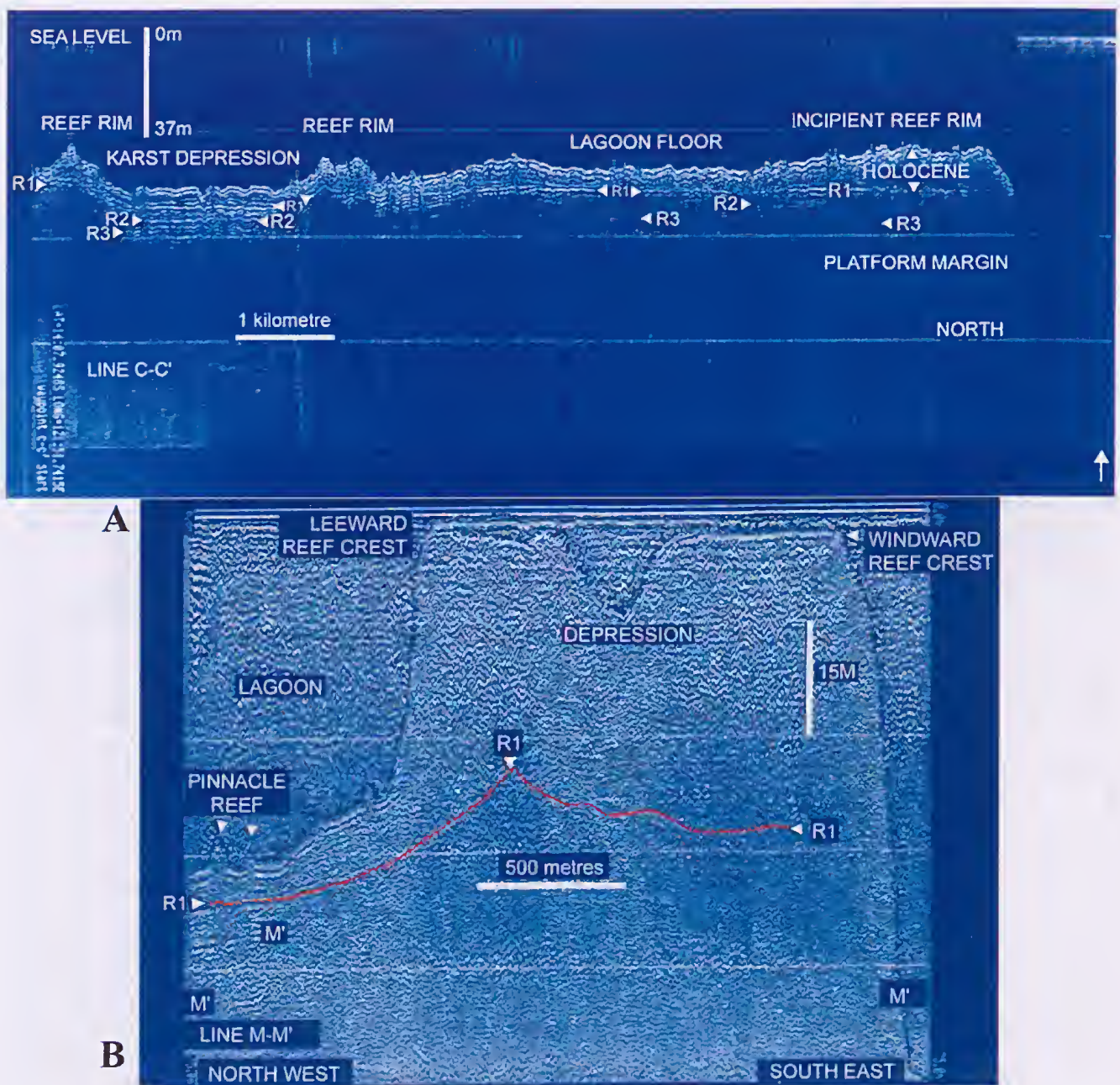


Figure 5. Seismic (boomer) architecture of Scott Reef platform (see Fig. 4 for location). A) Section C-C' of South Reef lagoon showing seismic discontinuities and karst depression. Three unconformities can be identified: R1, R2 and R3. R1 corresponds to the Last Interglacial (top MIS 5e) surface, underlain by MIS 7 and 9. B) South Reef boomer profile M-M' across reef crest (see Fig. 4 for location). Note presence and elevation of R1 beneath the Holocene reef crest (from Collins 2002).

Holocene Reefs, Characteristics, Sea Levels

Contemporary reef morphology results largely from Holocene reef growth (with antecedent influences) and the Holocene (MIS1) preserves a detailed sea level, chronological and growth history record at Scott Reef (Figs 6 and 7).

Global Sea-level during the Holocene (MIS1)

Since the Last Glacial Maximum, some 19 ka ago, deglaciation has been accompanied by a series of meltwater pulses which have influenced sea-level rise rates and reef growth responses, including drowning events. There was a prominent drowning gap in reef

growth worldwide following Meltwater Pulse 1B. Subsequently during Holocene time some 40 m of vertical reef growth (*e.g.*, 35.9 m or 44.1m LAT; with reef initiation at 10.6 ka ago in SE BH6-J) has occurred at Scott Reef (Figs 6 and 7).

The Indo-Pacific reef growth phase (termed RG111) was characterised by moderate rates of sea level rise of 10 mm/year (generating "keep up" or "catch up" reefs) from 11 to about 7–6.5 ka BP until sea level stabilization at or 2 m above its present position (Pirazzoli 1996). However, short periods of rapid sea-level rise, such as the 6m jump at 7.5 ka of Blanchon *et al.* (2002), with accompanying pauses in reef growth, have been reported elsewhere. The dated Holocene cores at Scott Reef

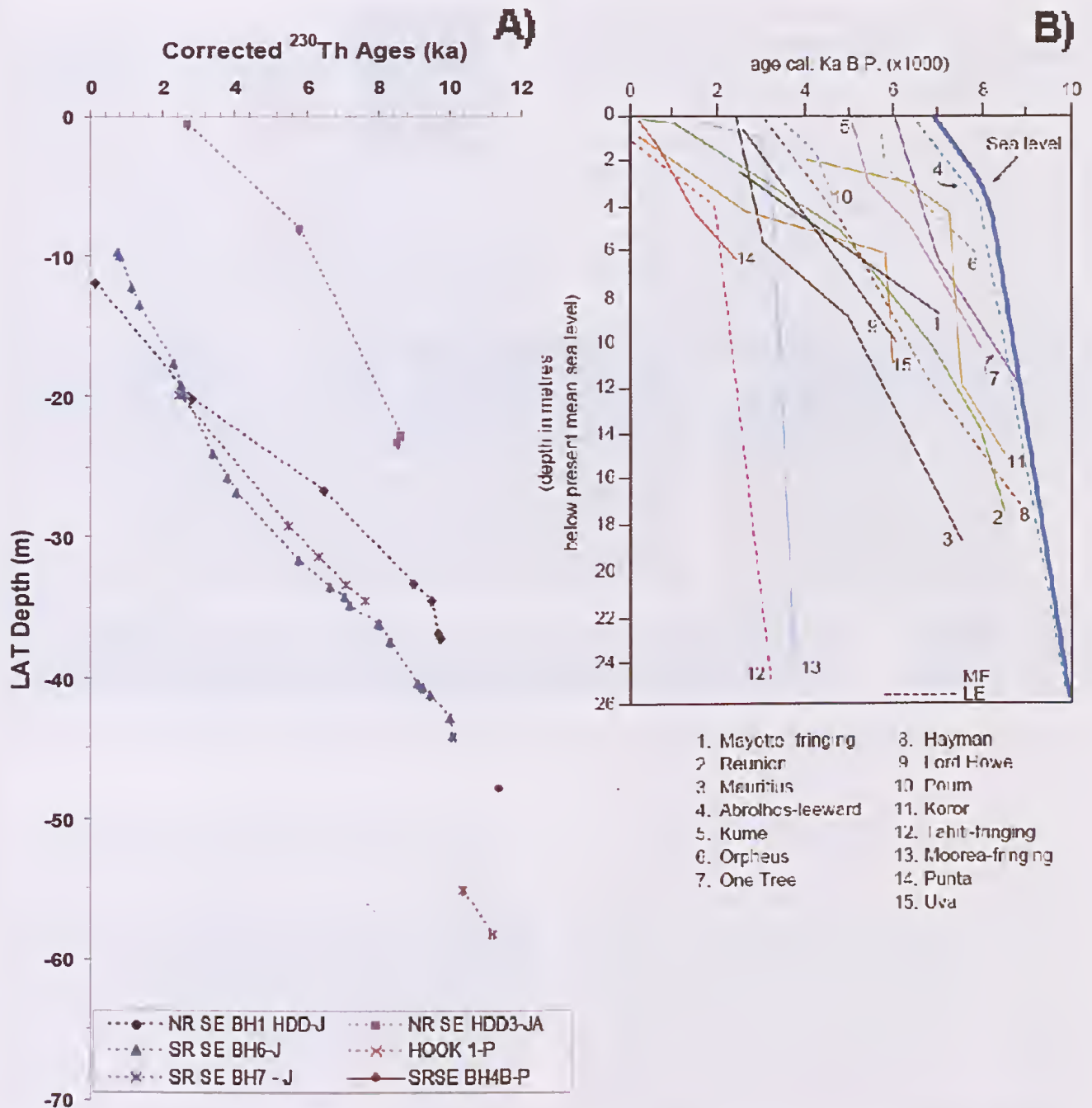


Figure 6. Comparative Holocene vertical accretion rates and curves related to Indo-Pacific reef development. A) Scott Reef dated cores. B) Selected growth histories of exposed Indo-Pacific reef crests/flats for the Holocene sea level rise (data from Montaggioni (2005, p.43), and references therein).

provide an opportunity to evaluate rates of sea level change and reef growth for reefs in different settings, both within Scott Reef, and between Scott Reef and reefs elsewhere (Figs 6 and 7).

Platform Morphology and Holocene Reef Initiation

The platform morphology that underlies the Holocene at Scott Reef is heterogeneous within and across North and South reefs. The irregularities generated during the erosional period that characterised the R1 hiatus are reflected in post glacial reef development as lower areas were inundated at the beginning of the event, whilst

higher areas record younger ages. In Scott Reef, the earliest dated settlement of a reef building coral community was recorded for the borehole HOOK 1-P at 11.5 ka at -58m L.A.T. depth, and for SRSE BH4B-P, in the vicinity of the inner crest of the South Reef, reef initiation was at 11.3 ka, and at -47.9m LAT depth and SRSE BH6-J at 10.1 ka (Fig. 7). At North Reef, earliest colonization date is 9.7 ka for NRNE BH1- HDD-J. All these reef onset ages postdate the 11.5 ka assigned to Meltwater pulse 1B thereby bracketing the Holocene growth phase to this particular meltwater pulse and subsequent sea-level rise.

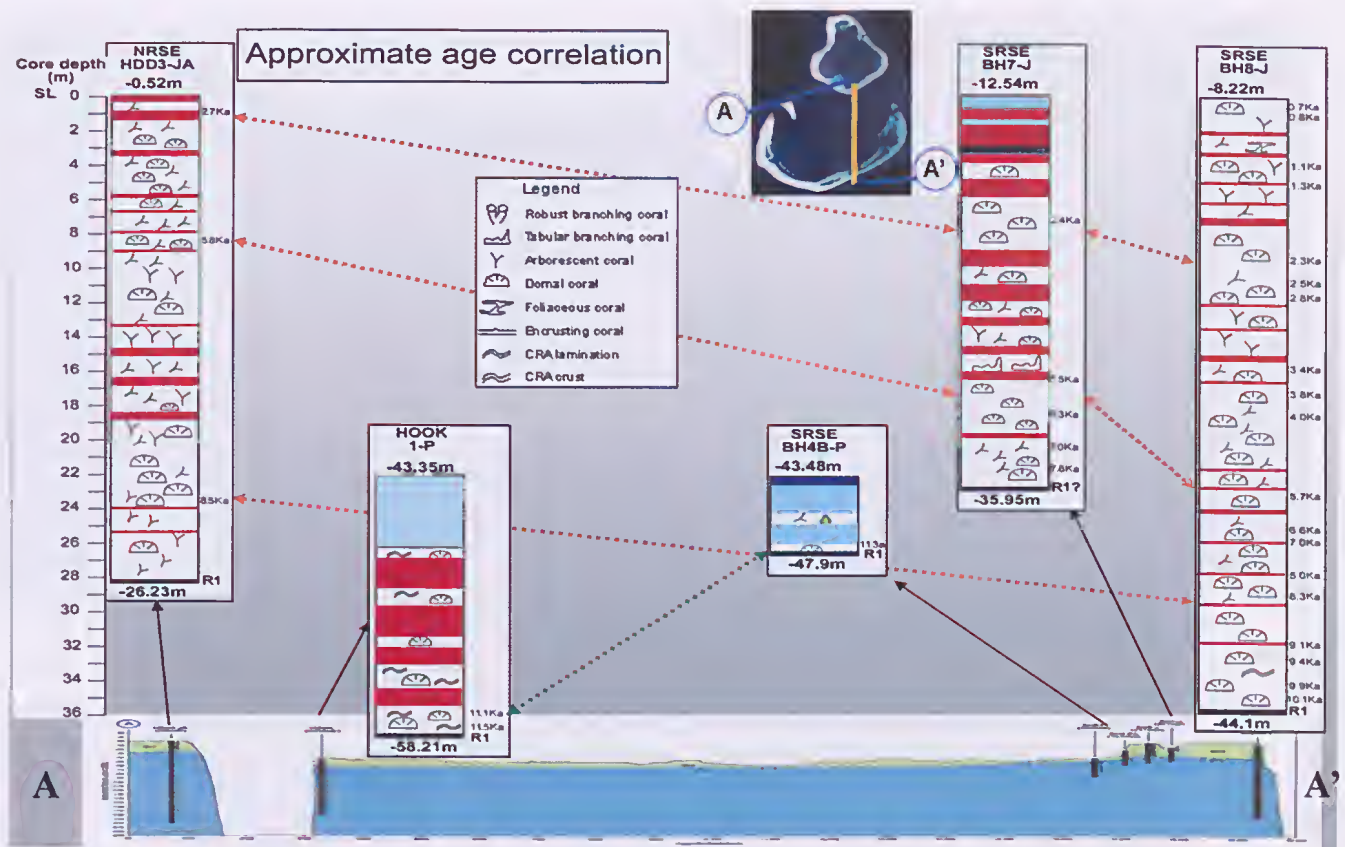


Figure 7. Summary of cored Holocene reef sections for Scott Reef showing major reef building communities. Note geochronology including Holocene reef initiation dates. All dates are expressed as U/Th ka (kiloyears) before present.

Rate of Holocene Reef Accretion

Accumulation rates were obtained using U-series dated material in relation to the thickness of the deposit. This necessarily included both original framework and reworked material. Accretion rates are expected to vary mainly related to three aspects: 1) regional occurrence of frame-building taxa; 2) primary frame building taxa related to the environment where the core is located; and 3) amount of reworked material locally generated (see Blanchon & Blakeway 2003, for discussion). This suggests that the nature of framework facies controls the accretion rates in reef environments (Montaggioni 2005). Rates and modes of reef growth vary greatly within the same reef system, according to the zone considered (Davies *et al.* 1985).

Most reefs investigated are frame-dominated structures, although reworked material is found in some sections. Reef accretion through the Holocene of Scott Reef varies from core to core. In frame-dominated reefs the accretion rate varied from a maximum of 3.57 m/ka recorded for SR SE BH6-J, to a minimum of 2.65 m/ka recorded for NR SE BH1 HDD-J. Most of the investigated cores with accretion rates within the same order of magnitude are formed by domal to arborescent coral facies.

Montaggioni (2005) suggested that domal and arborescent reefs appear to have similar growth rates, however higher accretion rates are found in cores containing a greater proportion of arborescent forms (see

also Webster 1999). At Scott Reef the accretion rates are consistent with domal facies dominated reefs, i.e., smaller than 7 mm/y.

The changes in accretion rate observed in SRSE BH6-J during the Holocene (see Fig. 7) is faster in the beginning and end of the Holocene and slower during the mid-Holocene, and this may be attributed to the change from more domal to more arborescent dominated reef facies in the latter 3000 yrs. Therefore the reef developed as a keep-up to catch-up reef, finally returning to a keep-up mode of growth towards the end of the Holocene. This suggests that both catch-up and keep-up signatures can occur in framework as well as detritus, in ocean-facing and sheltered reef flats, in a given period of time.

In a regional assessment of core data from Indo-Pacific reefs, including the Houtman Abrolhos and Ningaloo Reefs (see Collins *et al.* 1993, 2001) a wide-ranging facies scheme was developed by Montaggioni (2005) and this provides the best reference framework available for evaluation of the Scott Reef communities and facies (rock) associations.

Framework facies are broadly grouped as high-hydrodynamic energy (calcareous red algae and robust-branching corals), moderate energy (domal, tabular-branching and arborescent corals), and sheltered areas (association of arborescent, folioseous and encrusting corals).

Based on maximum rates of vertical accretion, the Indo-Pacific reefs can be classified into (1) fast-growing

reefs, with rates up to 10 mm/year. Such rates can be sustained for 3–5 ka and may reach up to 20 mm/year for periods of about 500 years. They result commonly in expanded sequences up to 25 m thick; (2) moderate-growing reefs, with rates of 5–7 mm/year, which generally produce sequences 10–25 m thick; (3) slow-growing reefs, with rates of 1–4 mm/year which commonly form sections less than 10 m thick (Montaggioni (2005)).

Reef margins have generally been considered to have lower accretion rates. The reasons why reef margins have developed slower vertically may be attributed to the settlement of slow growing corals or due to the higher hydrodynamic energy promoting lesser coral larval settlement. Accretion rates determined for Scott Reef are within slow-growing reefs, with rates of 1–4 mm/year, which commonly form sections less than 10 m thick. However the Scott Reef Holocene thickness approaches 40 metres.

Vertical accretion potential can be converted to net calcification (see Smith, 1983), a measure of carbonate production expressed in $\text{kg CaCO}_3 \text{ m}^{-2} \text{ year}^{-1}$, taking into account a value for the porosity of the original framework and detritus fabric (about 50%) and the density of an aragonite and calcite mixture (about 2.89 g/cm^3). Thus, slow-growing reefs should range from $1\text{--}3 \text{ kg m}^{-2} \text{ year}^{-1}$. To date no studies have been done of calcification rates at Scott Reef, however it would be interesting to pursue this line of research in the light of predictions of future climate change and increasing ocean acidity.

Reef Response to Holocene Sea-level Rise

Holocene reef growth history curves are presented in Figure 6A. The Scott Reef cores are unique in that they provide an uninterrupted history of reef growth throughout the rising deglacial sea-level of the last 10,000 years, with precise U-series dates and little “noise” in the data. Four cores were documented fully and one (NRSE HDD3-JA) was dated on a reconnaissance basis. The 3 fully dated cores (NRSE BH1 HDD-J, SRSE BH6-J, SRSE BH7-J) “cluster” and have similar gradients, however NRSE HDD3-JA is distinctly older though less completely dated.

At -20 m LAT there is a “crossover” and thereafter the outer reef (SRSE BH6-J) grew more rapidly than the inner reef (SRSE BH7-J), probably due to changes in coral community, for southeast South Reef between -20 m and -10 m, where the data ends. The top 10 m of history is not recorded because the SRSE BH 6-J borehole was sited in 8m water depth, seaward of the reef crest, and BH7-J lies in a depression between the inner and outer reefs.

Core NRSE HDD3-JA represents a near-reef crest setting in southeast North Reef, and the data are recorded to close to sea-level. As a consequence this core provides the best data on reef crest growth rates, and most closely provides a proxy sea-level record. On this basis the crest of southeast North Reef (and the rising sea-level) reached close to present sea level (-1.5 m LAT) by 2.7 ka ago. Coral reef records in southwest Australia record a brief sea level highstand of about +2 m some 7 ka BP (Collins, 1993, 2003; Houtman Abrolhos and

Ningaloo Reefs; both microtidal systems), followed by a decline to present sea-level, but there is no data at Scott Reef to support this.

A comparison between the Scott Reef data and growth history records for 15 documented reefs is shown in Figure 6B. Many growth history records lag behind sea-level, probably as a function of position of the core in the reef system, and the lag depth between sea-level and the particular reef community dated (for example *Acropora palmata*, which grows close to sea-level, is absent from Indo-Pacific reefs). The best sea level “fit” is curve 4 (Abrolhos reefs).

The dated onset of Holocene reef growth sheds some light on the relationship between the inner and outer reefs which form the “double reef” of the South Reef platform, though this information is incomplete. The shape of the antecedent surface (the R1 reflector; the eroded and possibly discontinuous, preceding reef crest of MIS 5) can be seen in seismic profiles (see Fig. 5). The elevation of this surface was an important control on reef initiation during sea-level rise. Because the outer reef had an early “start-up” date (10.1 ka) due to its position on the relatively deeper outer platform margin, and given the lag time of about 1000 years for reef “start-up” it is likely that the outer reef was well advanced before initiation of the inner reef occurred from shallow start-up depths. More U-series dating results will likely resolve this question.

Frame Builders of the Holocene Reef

The upper (Holocene) phase of reef growth, reef building communities, available U-series dates and core transect locations are shown in Figure 7. A range of reef settings, including reef front, west-facing, south-facing and east-facing reefs, back reef, and reef channel are represented. A data gap in Indo-Pacific reef studies is the lack of ocean-facing reef cores, so the presence of at least 6 such cores from Scott Reef provides a rare opportunity to address this deficit.

Most cores are composed of porous but relatively unaltered reef framework with lesser amounts of carbonate sediment; some intervals, particularly those of branching corals, are rubblely, partly as a result of disruption by rotary drilling, and partly as a result of accumulation of both “framework” and “fill” material.

The dominant frame builders are communities of arborescent (branching) corals, and domal (massive) corals (including *Porites*); these exist as end member communities as well as in mixed associations, as in cores SRSE-BH7-J; 6-J; NRNE-BH1-HDD-J; NRSE-HDD3-JA (Fig. 7). In SRSW-BH1-J there is a distinctive assemblage of robust branching corals and coralline algae, and in NRCH-BH1-J tabular branching corals, *Halimeda* and coralline algae are significant. In a regional assessment of 30 years of core data from Indo-Pacific reefs by Montaggioni (2005) framework facies are broadly grouped as high-hydrodynamic energy (calcareous red algae and robust-branching corals), moderate energy (domal, tabular-branching and arborescent corals), and sheltered areas (association of arborescent, foliaceous and encrusting corals). Scott Reef can be summarised as high energy; cyclone-influenced, swell-wave influenced and

tidally dominated. Its 4 metre tidal range is at the high end of Indo-Pacific tidal energy conditions. Its cyclone exposure is significant, as illustrated by the boulder field that constitutes the outer reef flat surface, and surrounds the fore-reef slope.

Wave energy is also significant, largely from westerly approaching swell waves, but the arcuate to circular reef orientation combined with wave refraction provides a spectrum of reef front wave energies, from high to moderate to low.

The most common community and facies association is of arborescent (branching) corals, and domal (massive) corals (including *Porites*); both as end member communities as well as in mixed associations in vertical profiles, and found in cores taken immediately seaward of the reef crest on the forereef (Fig. 7). It represents, for the arborescent association, sheltered settings (at 0–20 metres) in lower to middle parts of the forereef, and for the domal association, a semi-exposed to sheltered, relatively deep environment of depth 10–15 m. This is the dominant reef building association in the South Reef southeast reef slope (SRSE-BH6-J), and the North Reef southeast reef slope (NRSE-HDD3-JA) which are relatively low-wave energy settings due to their southeast facing aspect. Core SRSE-BH7-J, situated on the inner reef slope at southeast South Reef, also has a similar assemblage, as does NRNE-BH1-HDD-J, (outer reef slope, relatively protected, northeast facing setting). In contrast, in SRSW-BH1-J an association of robust branching corals and encrusting coralline algae is significant (representing high hydrodynamic energy environments; Montaggioni, 2005) together with the assemblage of domal and arborescent corals of lower hydrodynamic energies. The outer reef flat to reef front of the southwesterly facing reef crest of South Reef has higher wave energies than more easterly facing settings, hence the presence of the high hydrodynamic energy indicator communities described.

The coral assemblage in NRCH BH1-J from the lagoon side portion of the tidal exchange channel which breaches the north facing reef of North Reef is relatively high in diversity, and includes tabular branching corals (open marine, moderate energy, depths <15 m), foliaceous corals, particularly in the lower part of the core, as well as domal and branching corals. Also present are *Halimeda* and calcareous red algae. Tidal channels are subject to high to very high tidal current velocities as part of the lagoon flushing process. Foliaceous corals are most prevalent in shallow back reef environments and this is also consistent with the setting of the core.

Core Hook 1-P was collected near the incipient reef rim which marks the northern most margin of the lagoon of South Reef (Figs 5A and 7). This reef is best characterised as a “give up” reef as it failed to grow to sea level. Analysis of the coral community, which apparently consists of domal coral and coralline algae, is limited by the very poor recovery in the core. Core loss intervals are likely to have consisted of unconsolidated sand and rubble, and this is consistent with the mixing of lagoon – derived sediment with the growing coral communities. Such an environment of high sediment supply and probably high turbidity may well have served to limit coral growth, and caused failure of the

reef to keep pace with sea level rise. It is currently blanketed by carbonate sand and lacks modern recolonisation.

Scott Reef Holocene (compared with results from Indo-Pacific reefs) provides a record of reef front communities rarely obtained due to access problems. The dominant coral community and facies association of arborescent (branching) corals, and domal (massive) corals (including *Porites*), both as end member communities as well as in mixed associations in vertical profiles, from cores taken immediately seaward of the reef crest on the forereef, represents, for the arborescent association, sheltered settings (at 0–20 metres) in lower to middle parts of the forereef, and for the domal association, a semi-exposed to sheltered, relatively deep environment of depth 10–15 m.

The moderate hydrodynamic energy conditions represented by these frame builders, (Montaggioni & Braithwaite 2009) may be due to the fact that the community record is one that lagged somewhat behind the rising Holocene sea-level, thus representing relatively deeper conditions than would be experienced in the upper 10 metres of reef crest deposition. One factor here is that a number of key cores (NRNE BH1-HDD-J; SRSE BH6-J, for example) do not capture the uppermost 10 metres of the reef crest in their record where significant amounts of coralline algae might be expected. Records of the uppermost portion of the reef flat (NRCH BH1-J; core top at -3.09 m LAT; SRSW BH1-J; core top at -2.77 m LAT) have encrusting coralline algae in the upper few metres, indicating high hydrodynamic energies at the reef crest.

Discussion

Scott Reef rises from depths of 400–700 m on the distal portion of a carbonate ramp. It is a complex of two large isolated coral reefs separated by a deep channel; the pear-shaped North Reef and the crescent-shaped South Reef. A cross section summarizing the relationships of reef building stages with the Scott reef platform is shown in Fig. 7.

The overall seismic architecture is a flat-topped platform bounded by platform margin reefs which flank steep marginal slopes, as reflected in the current day surface environments. There are distinct cycles of upward platform growth which resemble “stacked saucers” in shape, each mimicking the previous cycle. Cycle boundaries are marked by platform-wide seismic discontinuities (R1, R2, and R3) which rise under marginal reef crests before falling steeply at the platform margins.

The internal architecture of reef building phases in North Reef and South Reef are similar, with the exception that equivalent horizons are shallower in North Reef. Age/depth plots indicate the average subsidence rate for South Reef is 0.45 m/ka, and for North Reef is 0.29 m/ka, suggesting differential subsidence is occurring, with a higher subsidence rate for South Reef. This is consistent with the observation that equivalent subsurface horizons lie at shallower depths in the North Reef platform, however seismic data is lacking for North Reef restricting the information for comparison.

The Holocene reef profile preserves a detailed sea level and growth history record. During Holocene time (MIS1; last 10,000 years) 14 to 35 metres of vertical reef growth occurred. In the Indo-Pacific this reef growth phase (termed RG111) was characterised by moderate rates of sea level rise of 10 mm/year (generating “keep up” or “catch up” reefs) from 11 to about 7–6.5 ka BP until sea level stabilization. Core NRSE HDD3-JA represents a near-reef crest core in southeast North Reef, and the data is recorded until close to sea level. As a consequence this core provides the best data on reef crest growth rates, and most closely provides a proxy sea level record.

The most common Holocene community and facies association is of branching (arborescent) corals, and massive (domal) corals (including *Porites*); present in close association, both as end member communities as well as in mixed associations in vertical profiles, and found in cores taken immediately seaward of the reef crest on the forereef. Hydraulically this represents, for the arborescent association, sheltered settings (at 0–20 metres) in lower to middle parts of the forereef, and for the domal association, a semi-exposed to sheltered, relatively deep environment of depth 10–15m. This is the dominant reef building association in the South Reef southeast reef slope, and the North Reef southeast reef slope which are relatively low wave energy settings due to their southeast facing aspect. Robust corals and coralline algae are important constituents of the higher energy forereef of southwest Scott Reef, and these corals represent high hydrodynamic energies.

Scott Reef is an isolated system which is tide-dominated, cyclone influenced and wave-influenced. The combination of core data from a range of reef crest and lagoon settings, together with the availability of shallow seismic data has provided a unique opportunity to develop a Holocene model for reef growth which is geologically significant whilst informing biophysical analysis and environmental management.

Acknowledgements: Initial sampling and seismic surveys of Scott Reef in 2000 by RV Franklin provided reconnaissance data on Scott Reef. The Curtin project team thanks the Captain, Crew and support from Australian Research Council, and shipboard assistance from CSIRO and Geoscience Australia researchers. Site test cores collected by Woodside Energy Limited formed the basis of the Scott Reef study in 2009, and a Woodside grant to Collins (Curtin) to study the cores (with Viviane Testa, Curtin) made this project possible. Luke Smith (WEL) is thanked for assistance and advice throughout the study. U-series dating at University of Queensland was completed by Zhao and Qu in a timely way, and Dr Yue-xing Feng is thanked for analytical support in the UQ lab. Andrew Shuckstes and Michael Page (Worley Parsons) provided advice in the early stages of the core study. Ms Alexandra Stevens is thanked for assistance during the study and with compilation of the paper. The first author thanks co-authors for their enthusiasm and support in the successful completion of the study.

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Reconnaissance of species-rich coral reefs in a muddy, macro-tidal, enclosed embayment, – Talbot Bay, Kimberley, Western Australia

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Abstract

Preliminary observations are presented on species-rich coral reefs in a mud-dominated, macro-tidal, virtually landlocked embayment on the Yampi Peninsula. The reef platforms stand 6–7 m above water level at extreme low spring tide. High lagoons on the top of the platforms, impounded by crustose algal terraces and banks of rhodoliths, provide habitat for a moderately diverse assemblage of scleractinian corals with up to 30% live cover. Reef flats in the lower-littoral zone around the periphery of the fringing reef platforms, and on small patch reefs scattered throughout the bay, support species-rich coral assemblages with live coral cover up to 90% even though heavily affected by mud. There is dynamic interaction between coral reef growth and the development of massive mud banks in the bay. Drilling will be required to determine the geological origins, age and composition of these massive reef structures. If they are entirely of Holocene construction they would represent a remarkably high rate of coral reef growth in such a mud-dominated environment.

Keywords: Kimberley, Talbot Bay, coral reef, reef origin, reef profiles, macrotidal, mud-dominated

Introduction

Although their presence has been known to science for almost two hundred years, the extent and species-richness of coral reefs in the Kimberley Bioregion (Cape Londonderry to Cape Leveque) of Western Australia has been revealed only during the last few decades. Little of the information now available has been published in the scientific literature.

This report presents preliminary observations on some remarkable reefs within Talbot Bay, an almost enclosed, macro-tidal, mud-dominated gulf on the northern side of the Yampi Peninsula. This part of the Kimberley is a ria coast with maximum tidal range round eleven metres and is characterised by extreme tidal fluxes and turbid water. Well developed coral reef structures occur in association with extensive intertidal and subtidal mud deposits and mangrove forests, in an environment typical of northern Australian macrotidal estuaries. Observations on these reefs are reported from a brief visit to Talbot Bay by staff and associates of the Western Australian Marine Science Institution (WAMSI) in September 2010, aboard the charter vessel *Olivia J*.

The purpose of the report is to draw attention to these remarkable reef structures and the equally remarkable biogenic activities that prevail there. These preliminary

observations suggest that future detailed studies of these reef systems are likely to reveal highly unusual reef-building processes and dynamic interactions between mud deposition and coral reef development that are perhaps without parallels elsewhere on the Australian coast.

Methods

Intertidal studies

At low tide, landings were made at reef sites selected using available Landsat 7 satellite imagery. Field activity was focussed primarily on a prominent reef structure known as Turtle Reef, which borders the rocky Molema Island, near the centre of Talbot Bay (Figs 1 and 2). The tidal range during the period of study is shown in Figure 3.

Reef elevation profiles, structure and biotic assemblages were recorded along line transects photographically (using a digital camera) at 1 m intervals. Six transects were completed, three on Turtle Reef South, one on Turtle Reef North, one on the south-western side of Mangrove Island, and one on a small patch reef in the channel off the NW corner of Molema Island (Fig. 4). Coordinates of these sites and basic transect data with summary descriptions are given in Appendix 1.

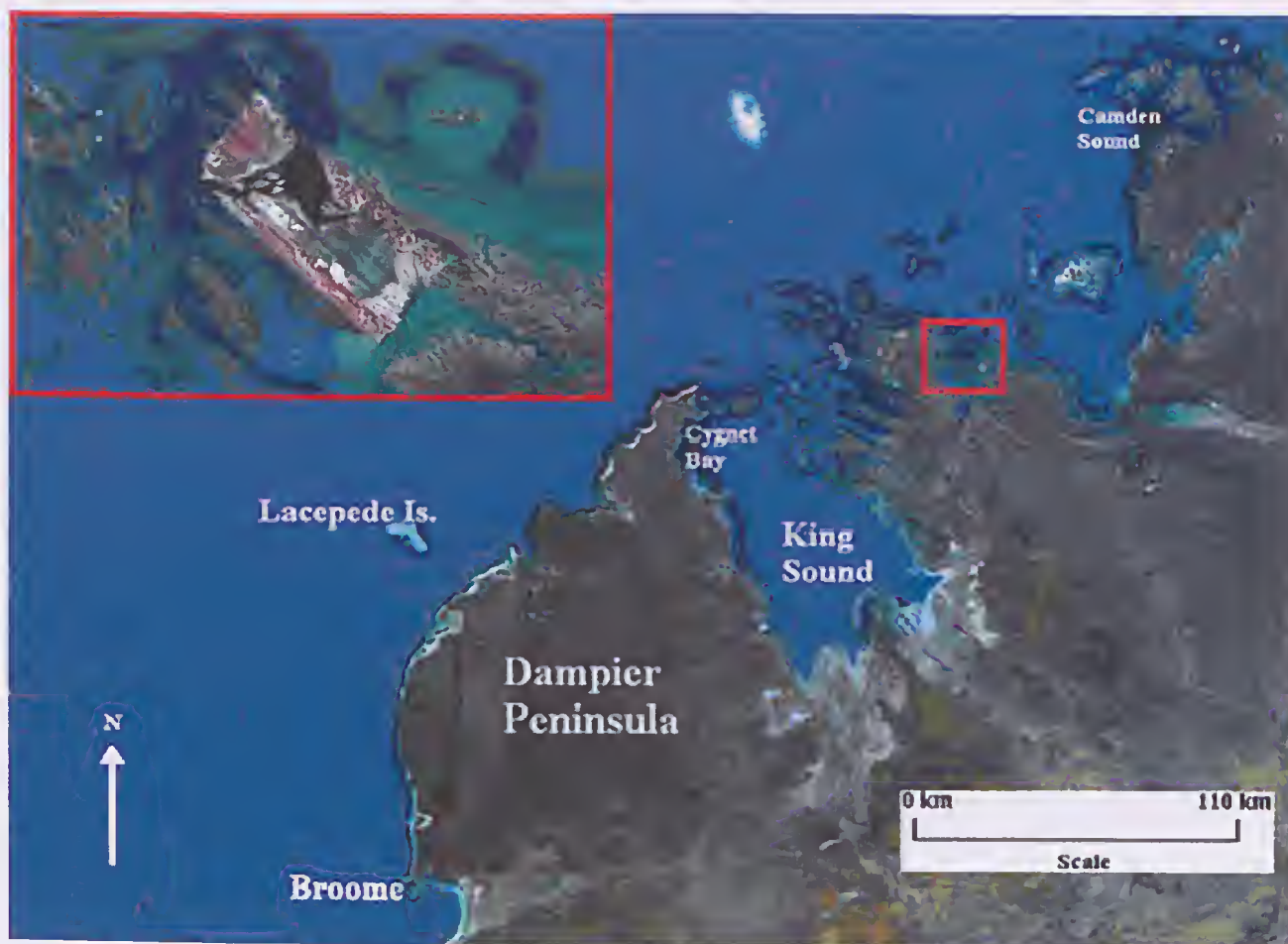


Figure 1. Location of Turtle Reef, Talbot Bay, Kimberley coast, WA. Inset: Airborne tri-colour mosaiced image of Turtle Reef. Most of the islands within the bay are un-named (but may have un-recorded indigenous names). The inset image gives an overview of the entire area surrounding Turtle Reef [Images: courtesy Google Earth and inset: Airborne Research Australia].

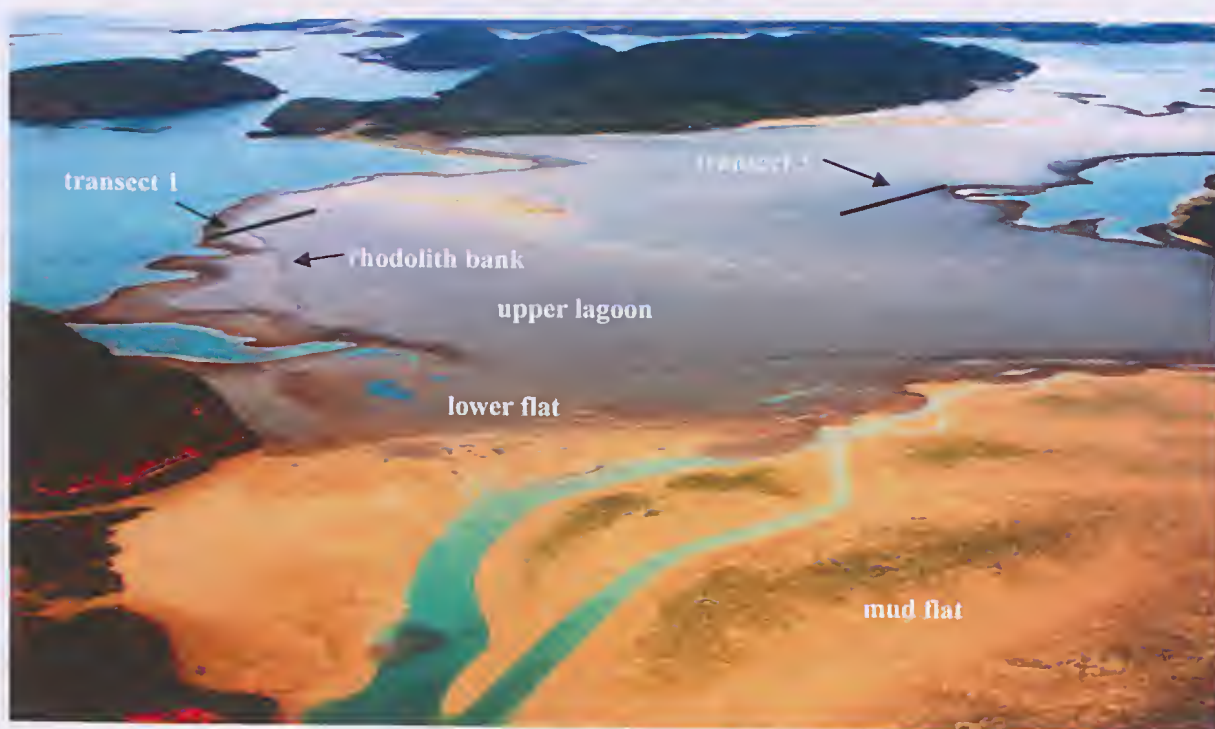


Figure 2. Low-tide aerial oblique view of South Turtle Reef, looking west. Molema Island is almost out of view on the right side. Note the massive mud bank in the foreground that overlaps the eastern margin of the reef platform [Photo: courtesy Kimberley Media and WAMSI].

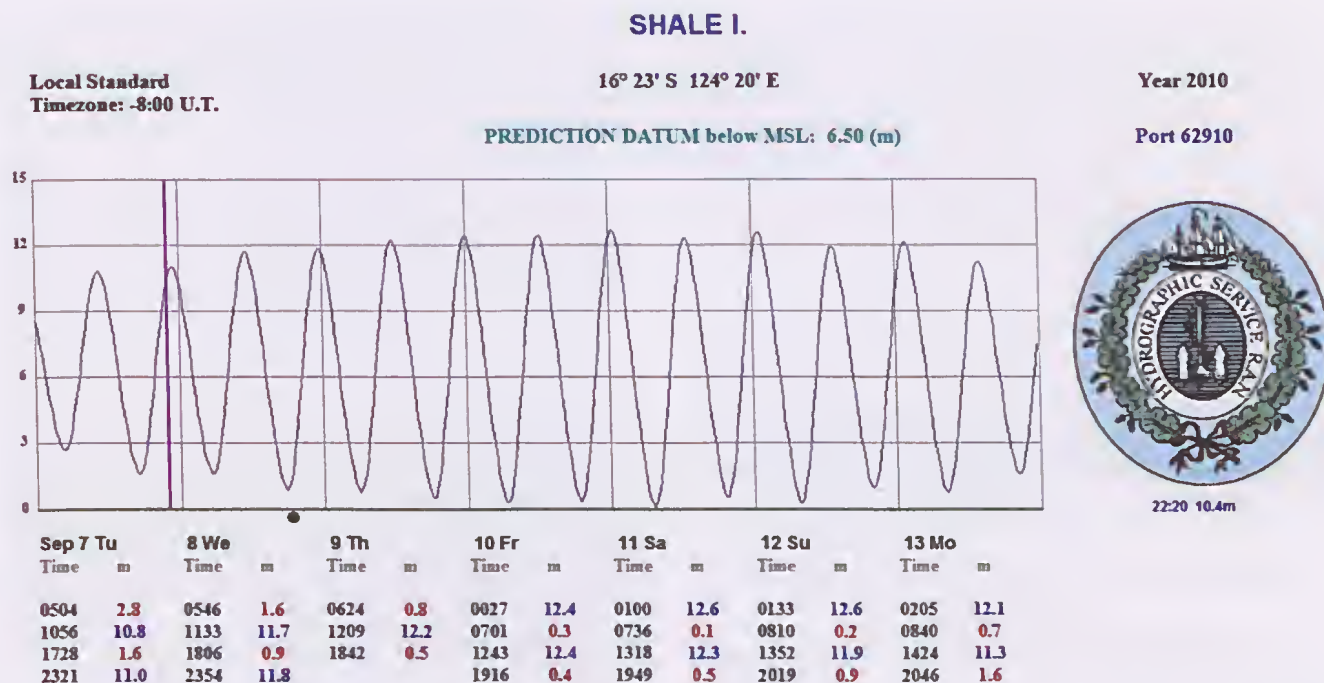


Figure 3. Hydrographic Service tide chart (Shale Island) for the period 7–13 September, 2010, the period of the Talbot Bay survey [Image: courtesy Australian Hydrographic Services, Royal Australian Navy].



Figure 4. Western end of Molema Island, looking south, at extreme low tide showing a large mud bank adjacent to the edge of a fringing coral reef. South Turtle Reef top left. Note the three small patch reefs in the channel, centre right (site of Transect 6). Site of Stuart photographs in the top right corner [Photo: courtesy Airborne Research Australia].

Aerial photographic and multi-spectral survey

We undertook hyperspectral airborne imaging of Turtle Reef and surrounding islands on a large spring tide [0.2 m] on 12 September 2010 at 0810. Coincidentally, we also took LIDAR, Tri-colour scanner and high resolution digital photographs of the study area. These data provide a high resolution digital base map that can be further interrogated for detailed spectral information and, in the case of LIDAR, vertical height data to 15 cm accuracies.

Ground truthing was undertaken with the aircraft being directly overhead, to allow for end-member determination via a spectral library and the associated atmospheric correction. Contoured images, derived from the LIDAR data, are presented for two of the survey transects to give a first impression of the relative altitude of the reef platform.

A brief history of coral reef science in the Kimberley

In the narrative of his Kimberley surveys aboard the hydrographic survey vessels *Mermaid* and *Bathurst*, British hydrographer Philip Parker King made mention several times of corals and coral reefs (King 1827). He published a list of 20 species of corals in his Appendix B, three of which he collected at low tide on a reef at the Midway Islands near the entrance to Munster Water. Many biological samples collected by King and his crew found their way into the collections of the Natural

History Museum in London but whether his corals were among them is unknown. If they still exist these specimens have considerable heritage significance as they may have been the first corals collected for scientific purposes in Australian waters.

John Stokes (1846) also noted the presence of coral reefs on the Kimberley coast in his narrative of the subsequent survey of the region by the *Beagle*. He had been asked by his friend Charles Darwin (they had been shipmates on the earlier *Beagle* voyage) to look for evidence of reef development and subsidence (Stokes 1846) but, unfortunately, he did not make any observations of that kind in the Kimberley (although he did in Queensland).

Coral collections were made by Bassett-Smith from Holothuria Bank, Baudin Island, Troughton Island in the north Kimberley and at Baleine Bank off Broome during the third Admiralty survey to the Kimberley aboard the *Penguin* in 1890 (Bassett-Smith 1899). English fisheries biologist W. Saville-Kent collected corals at the Lacepede Islands, King Sound and Roebuck Bay in 1894. The *Penguin* and Saville-Kent coral collections are preserved in the Natural History Museum (London) and were used extensively in subsequent taxonomic research.

E.J. Stuart (1923) reporting on findings of an exploratory expedition on the West Kimberley coast, published photographs of fringing reefs in Dugong Bay (an inner inlet of Talbot Bay). One of the Stuart photographs is reproduced here, scanned from the publication (Fig. 5).



Figure 5. One of two photographs published by Stuart (1923) taken in 1917 at the reef edge at a site "west of the entrance to Dugong Bay". Stuart wrote that dynamite was used to blow away the outer wall to drain the water and allow this picture to be taken. [Scanned from the original publication, Stuart (1923)]

University of Western Australia geologists Curt Teichert and Rhodes Fairbridge (1948), working from military aerial photographs, described in detail the geomorphology of a large platform reef surrounding Adele Island. They also noted "ordinary fringing reefs ... in great profusion around most of the offshore islands and on many parts of the mainland coast". Following that work, Wilson (1972) distinguished between the shelf-edge atolls, offshore banks and platform reefs of the Sahul Shelf and the fringing reefs of the Kimberley coast as separate coral reef provinces.

A report on Western Australian corals by Veron & Marsh (1988) included an account of Kimberley corals, based mainly on literature references and collections made by staff of the Western Australian Museum. Coral species collected during later surveys of Kimberley coast were listed in unpublished W.A. Museum reports (Marsh, 1992; Blakeway, 1997). Those reports included the first descriptive accounts of the structure of fringing reefs of the region (Blakeway, 1997; Brooke, 1995, 1996, 1997). Subsequently, Dr Veron has provided preliminary data on the corals of the Kimberley coast in an on-line spatial database, *Coral Geographic*, dealing with the coral faunas of the world's "coral bioregions".

There is detailed information, most of it not yet in the public domain, on some of the extensive fringing reefs in the Bonaparte Archipelago, resulting from environmental assessment work in that area during the period 2006–2007 (RPS, unpublished reports to INPEX). That work included an intensive collecting program to document the coral fauna of the region. One paper on spawning of corals in the archipelago, resulting from those surveys, is in press (Rosser and Baird *Proceedings of the 11th International Coral Reef Symposium*, Ft. Lauderdale, Florida, 7–11 July 2008, Session number 11).

Regional geology and coastal geomorphology

The Yampi Peninsula is the intensely folded western end of the King Leopold Orogen (Yampi Fold Belt) a complex band of Proterozoic metamorphic and igneous rocks bordering the south-western side of the Kimberley Basin. Its elongate valleys were inundated by the last post-glacial transgression to form the rocky ria coast of the area and the adjacent islands of the Buccaneer Archipelago. Details of the geology of the Yampi Peninsula may be found in the maps and explanatory notes of the Bureau of Mineral Resources Yampi map sheet (Tyler & Griffin 1993).

The coastal geology of the peninsula is dominated by the Palaeoproterozoic metasediments and igneous intrusive rocks of the Kimberley Group. The geology of Talbot Bay, located on the northern side of the peninsula, is complex. The rocks of its shore-line comprise intensely deformed and highly resistant quartz sandstones of the Pentecost, Warton and King Leopold Sandstones, Elgee Siltstone and the Yampi Formation, with minor exposures of the tuffaceous Carson Volcanics.

Throughout the Kimberley Bioregion, there is no evidence of marine Pleistocene rocks or erosional notches on shore (Brooke 1995). Coral reefs appear to comprise upward growing coral and algal sequences, suggesting a significant thickness of Holocene limestone overlaying an

unknown foundation and ultimately supported by a Palaeoproterozoic basement. The lack of exposure of Pleistocene reefs in the Kimberley Bioregion may be explained as a result of Late Quaternary subsidence. There is evidence that the northern part of the North West Shelf of Australia has undergone prolonged, tilted subsidence. Teichert & Fairbridge (1948) illustrated this notion with a diagram showing the modern inclined shelf, the shelf-edge atolls and outer shelf platform reefs as carbonate bioherms of considerable antiquity and depth, and the inner shelf platform and fringing reefs as shallow Quaternary carbonate deposits over the Proterozoic basement. Sandiford (2007) suggested that the northern continental margin has tilted and subsided since the late Neogene at significant rates. The combined effects of ongoing subsidence and sea level change during the Quaternary would have enhanced the development and growth of fringing reefs in the Kimberley through providing 'accommodation space' for upward growth.

Coral reefs of Talbot Bay

Coral reefs within the landlocked inlets of Talbot Bay were first noted by the veterinarian E.J. Stuart in 1923, however his descriptions and photographs remained unreported by reef scientists until now. Indeed, due to the extreme macro-tidal and turbid water conditions of this environment, the presence of significant and flourishing accumulations of coral framework would appear to contradict established models for coral reef formation. The geomorphology of these reefs appears to be unique. Turtle Reef alone is over 25 km² in area, comprising a high carbonate platform in the middle-upper littoral zone (Figs 1 and 2) representing very large depositions of material that require an explanation.

The shores of Talbot Bay are predominantly rocky, steep and cliffed (Fig. 4) and the high relief of the landforms are matched by extremely complex subtidal bathymetry in bays and passages, with depths changing abruptly from shoals to channels that are over 30 m deep in places. Navigation is hazardous. At high tide the shoals and reefs are invisible because of the turbid water. The complex bathymetry and extreme tidal range result in exceedingly strong tidal currents, local shears and whirlpools, particularly during spring tides. The shoals include scoured rock reefs, coral reefs, sandbanks and mudbanks. There are several small freshwater streams that seasonally drain into the bay, but overall fluvial input is negligible. Sandy beaches are lacking. Most of the bays are lined with mudflats and a mangrove fringe, with several extensive mangal environments developed on mudbanks, the largest (Mangrove Island) supporting some 2.5 km² of mangroves.

Fringing coral reefs are prolific around the islands and peninsulas through the centre of Talbot Bay from the mouth of the inner Dugong Bay to the cluster of islands and banks (called the Mangrove Islands by our party) that lie across the main entrance from the open sea. There are also numerous and very dangerous small patch reefs scattered throughout the bay that emerge at low spring tide.

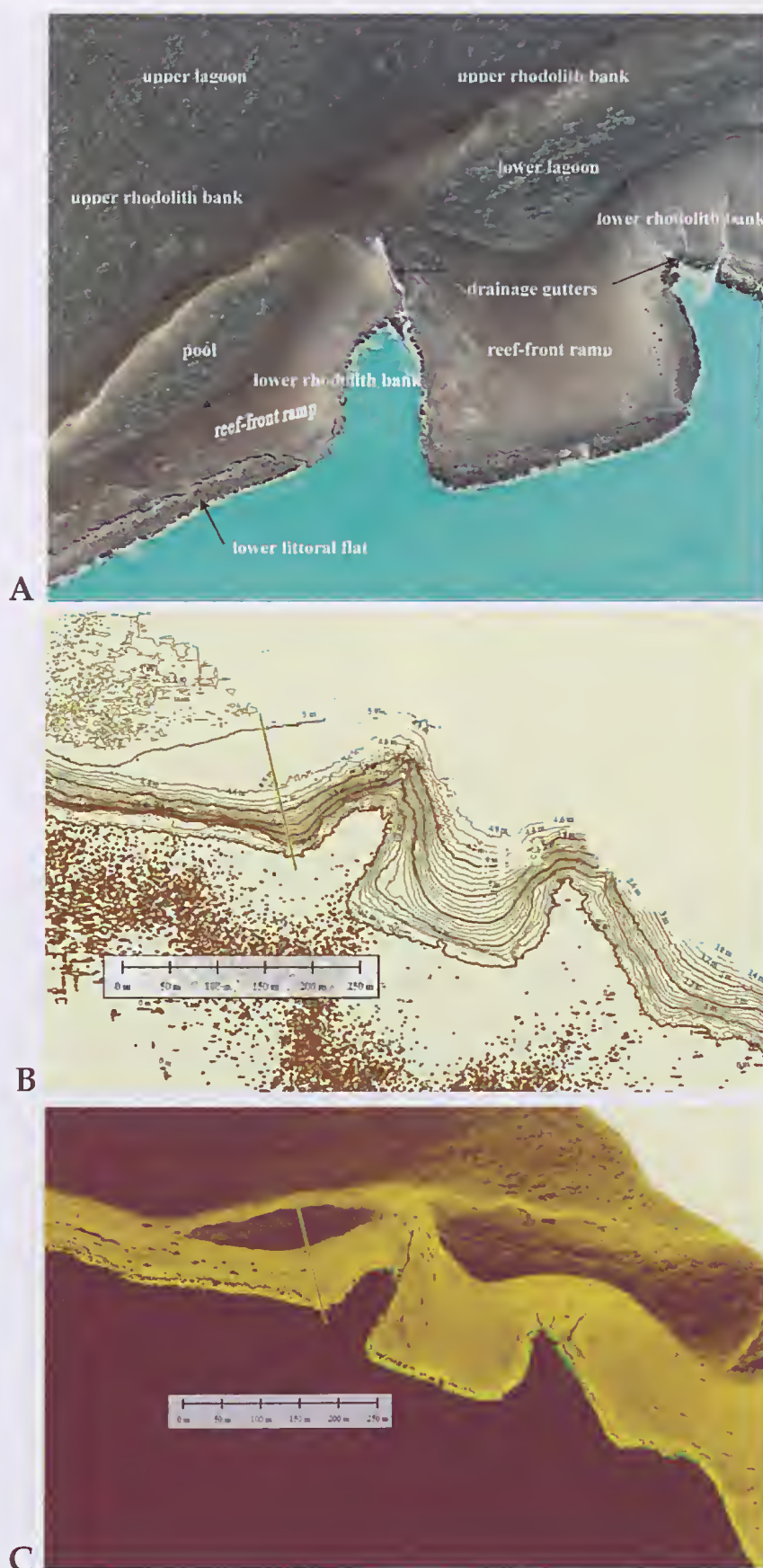


Figure 6. Transect 1, southern margin of South Turtle Reef. A) High resolution digital photograph of the lower portion of the transect from the lagoon, across a double rhodolith bank with a shallow pool between, the reef-front ramp and a narrow lower-littoral flat at the water's edge. Note small drainage gutters across the ramp and the narrow lower-littoral flat, just a few metres wide, at its base. B) Contour map of the same area derived from LIDAR data. C) NDVI image of the same area showing areas of intense photosynthetic activity. [Images: courtesy Airborne Research Australia].

The 1917 site of Stuart

In his narrative of the 1917 Kimberley expedition, Stuart (1923) described and photographed a coral reef, rich in coral species and other marine life, west of the entrance to Dugong Bay. On the mainland shore at this location there is a high, north-facing hill of Pentecost Sandstone and several small rock islands nearshore, with a wide, intertidal rock platform extending north-east along the shore for some distance.

On September 13, 2010 a landing was made by our party on the rock platform (co-ordinates 16°17.801'S; 123°50.293'E). From the profile of the mainland skyline to the south (Fig. 5) this was judged to be close to the site where the Stuart photographs were taken of the coral-rich reef edge (Fig. 3). At the time this reef was inspected by the WAMSI party the tide was half way in. The exposed platform surface, judged to be in the mid-littoral zone, was hard pavement with a cover of crustose algae and a sparse algal turf. Only a few small coral colonies were present. The reef edge was not visible but soundings indicated an abrupt step to a subtidal terrace and then another abrupt step to the seabed at around 30 m (below MSL). For historical reasons a repeat visit to this location would be worthwhile, during a period of low spring tide when the reef edge could be inspected and compared with Stuart's photographs.

Turtle Reef (Figures 1, 2, 4, 6 and 7)

For working purposes the survey team referred to the platform north of Molema Island as North Turtle Reef and the platform south of it as South Turtle Reef, although the two platforms are not connected. From the LIDAR data contour maps, contour maps and pictorial images have been prepared for the areas of the reef surrounding Transects 1 and 3 on South Turtle Reef (Figs 6 and 7). Summaries of observations made along the transects are given in the Appendix. The following are general notes on our field observations.

Reef structure

There were no exposures of the basement rock of the reef, the entire surface being covered by recent carbonates, comprising extensive rhodoliths, corals, sand, rubble or mud. Given the horizontal nature of the coral platforms which abut the steeply dipping Proterozoic rocks along the sides of the adjacent islands, it is assumed that basal layer is flat-lying and has a sedimentary origin but its nature and age are unknown. The several possibilities are discussed below.

Reef form

North and South Turtle Reefs are very large, high, platforms on either side of Molema Island, connecting that island on its northern side with the outer peninsula (Fig., 4) and on its southern side with smaller un-named islands about in the centre of Talbot Bay (Fig., 1). The total area of the reef platform is estimated at over 25 km².

The platform top appears more or less level, perhaps slightly undulating and a little higher on the southern side, and positioned close to the middle/upper-littoral boundary. On South Turtle Reef the heights of the reef crests were measured (from the LIDAR data) as 4.3 m at Transect 3 and 5 m at Transect 1. The height of the

platform overall, with its shallow lagoon, is estimated to be about 4.5 m above Spring Low Tide level.

The outer perimeter of the platform is defined by a steep, convex ramp with a succession of small terraces constructed by crustose algae (Fig. 8). The ramp slope varies from about 25° (e.g., at Transect 3) to about 10° (e.g., at Transect 2). It lacks significant coral growth except for a few small prostrate, mainly faviid colonies (< cm diam.). Our survey party was not equipped to investigate the depth of the algal crust but it seemed to be superficial.

Around the reef perimeter there are low areas in the ramp functioning as drainage channels. Some of these are wide with violent cascades of water run down them off the impounded lagoon of the platform above (Fig. 8). Others are minor rivulets or narrow gutters incised into the ramp surface (e.g., at Transect 1; Fig. 6A). There are usually fans of sand and rubble deposits along the base of the ramp, especially where minor drainage channels spill onto the lower terraces (Fig. 7A).

The top of the ramp is defined around much of the reef perimeter by one or more crustose algal ridges and sometimes bands of rhodoliths that impound the water on the reef platform. This is interpreted as the equivalent of the reef crest of most fringing reefs but is atypical – it is very high in the intertidal profile and there is no boulder zone. At some locations, for example on the north-eastern margin of North Turtle Reef the rhodolith bands along the crest are configured into inter-lacing patterns enclosing networks of small lenticular pools (Fig. 9). It appears that the rhodoliths are mobile and that their arrangement probably changes constantly with flux of the tide. At some locations (e.g., Transect 1) the reef crest is divided into two prominent rhodolith banks with a shallow pool between them (Figures. 6A and 6C). In these regards the Turtle Reefs are very like Montgomery Reef.

Around the margin of most of the reef, at the base of the ramp there are low flats at around the zero tide level. They are between five and fifty metres wide and exposed only briefly at extreme low tide. Along the southern margin of South Turtle Reef the low terrace is only a few metres wide in most places (e.g., Transect 1, Fig. 6Aa). On the northern margins of South and North Turtle Reefs, the lower littoral flats were usually much wider and represent a lower littoral reef flat (e.g., at Transect 3, Fig. 7A). At both transects, there is a small but distinct erosional escarpment at the base of the ramp, 10 to 30 cm high, marking the edge of the lower flat. Coral growth is prolific in this lower zone wherever this structure is present, clearly resulting in outward growth of the reef, and it is interpreted as the equivalent of the coral-rich reef-front of most fringing reefs. The fore-reef below the lower terraces is very steeply inclined or vertical and soundings of more than 30 m were taken close to the reef at many locations.

There are deep holes (> 5 m) in the lower terraces at several locations (e.g., at Transect 3, Fig. 7A) with very rich coral growth around their edges and vertical walls. The site of the Stuart photographs near Dugong Bay was probably a structure of this kind. (He described blowing out the wall with dynamite to drain out the water so that the corals were suitably exposed for his purpose!). These deep holes are assumed to be the outcome of coral

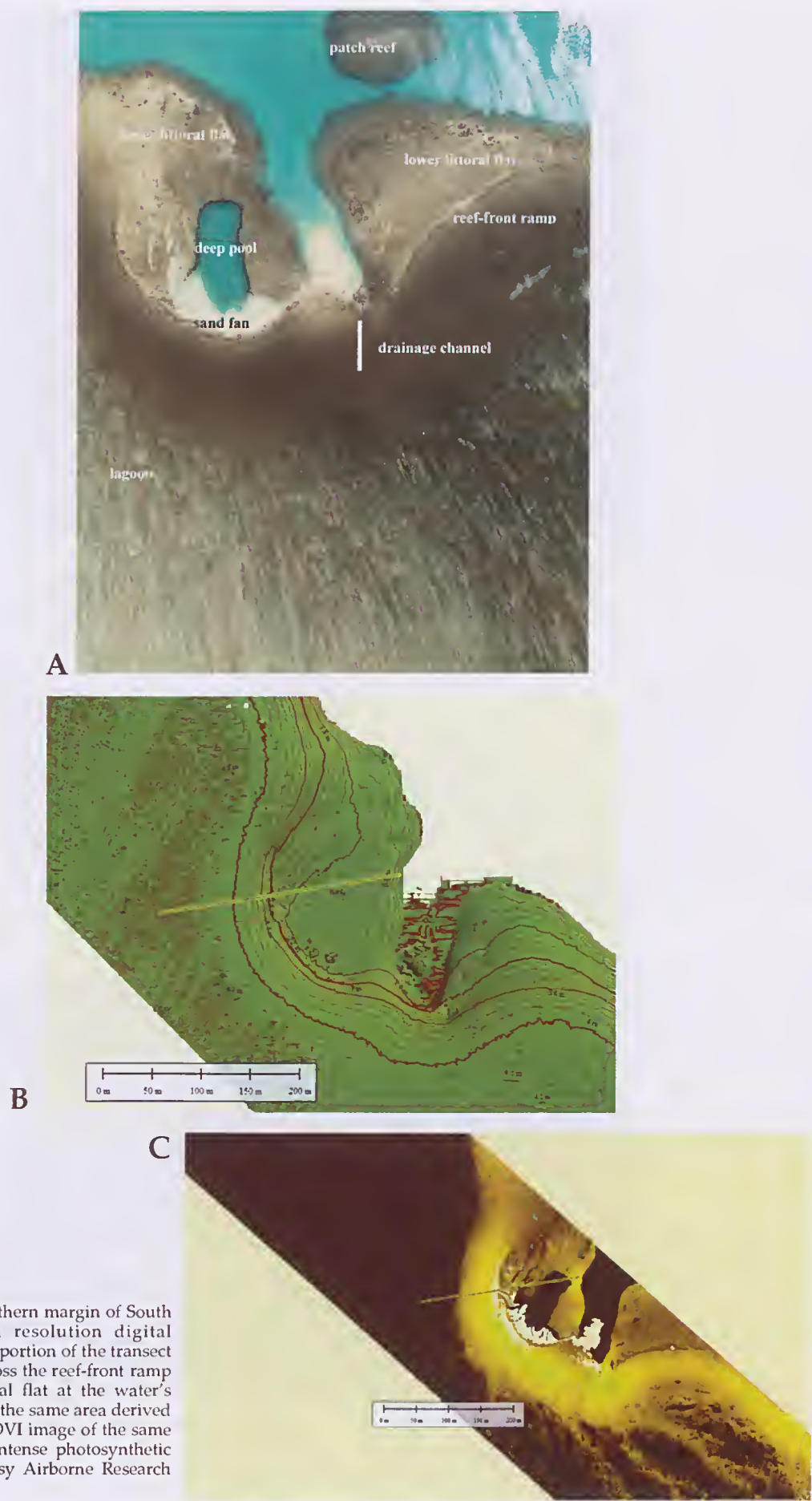


Figure 7. Transect 3, northern margin of South Turtle Reef. A) High resolution digital photograph of the lower portion of the transect from the lagoon and across the reef-front ramp and a wide lower-littoral flat at the water's edge. B) Contour map of the same area derived from LIDAR data. C) NDVI image of the same area showing areas of intense photosynthetic activity. [Images: courtesy Airborne Research Australia].



Figure 8. Western end of South Turtle Reef. One of many low-tide waterfall cascades down the ramp [Photo: S Blake, WAMSI].

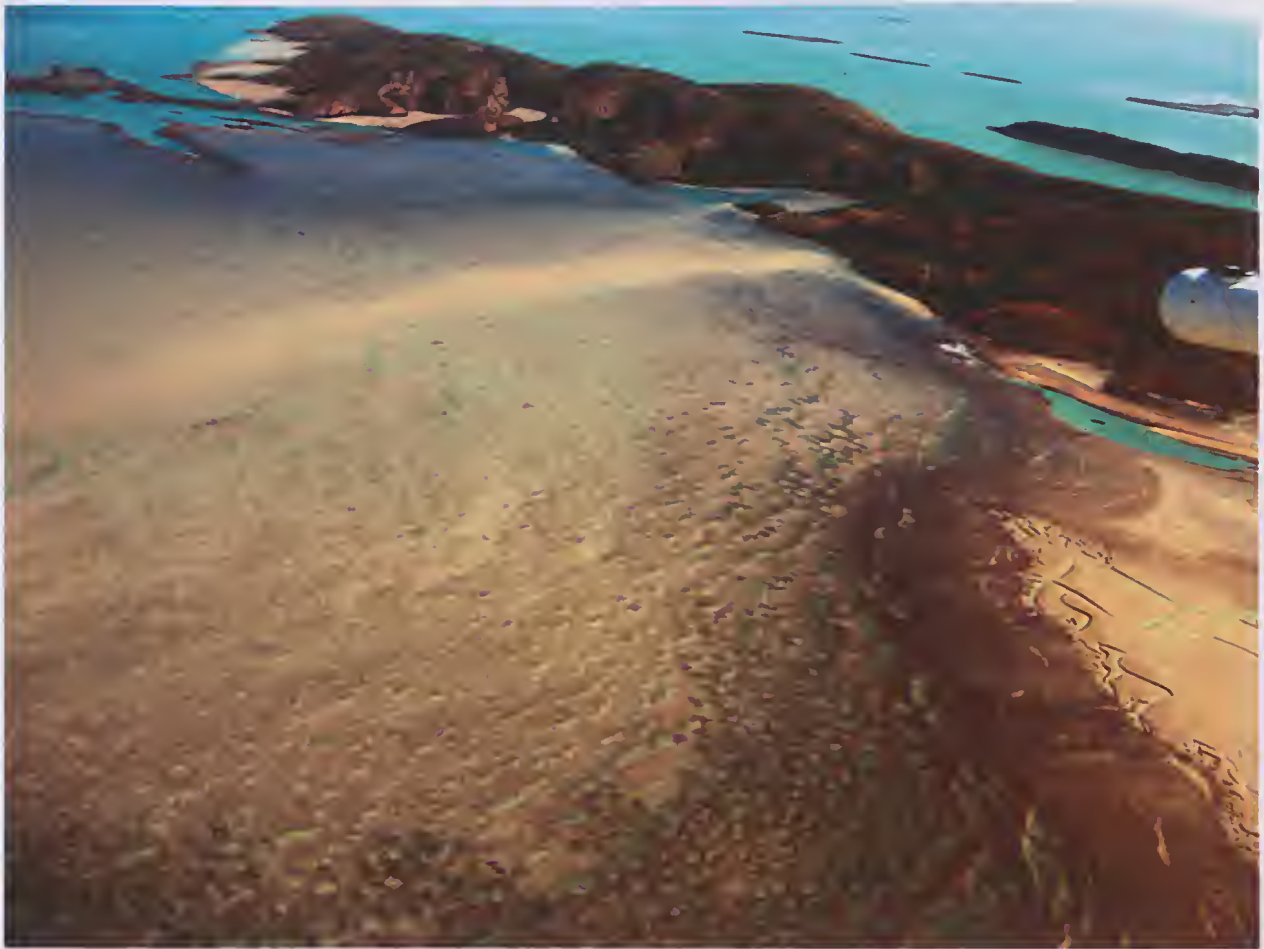


Figure 9. Eastern side of North Turtle Reef, looking north across the peninsula to the open sea. Showing rhodolith banks enclosing lenticular pools behind the ramp, abutting a mudbank [Photo: courtesy Airborne Research Australia].



Figure 10. Mud bank on-lapping the eastern margin of South Turtle Reef (see aerial view of the same place at Figure 2). [Photo: S Blake, WAMSI].



Figure 11. *Porites* micro-atolls in-filling pools on the high reef platform, close to Transect 3, South Turtle Reef. [Photo: S Blake, WAMSI].

growth across drainage channels or embayments in the reef margin. In Figure 7A at Transect 3 there is a deep hole alongside a deep drainage channel and is easy to imagine that the hole was an earlier drainage channel now enclosed by coral growth.

On the eastern side of the Turtle Reefs, both North and South, there are huge mud banks which overlay the edge of the reef (Figs 2 and 10). The mud is very soft and it was impossible to walk on it without sinking down to the waist. At the sharply demarcated margin of mud and reef there is evidence of the former overlapping the latter but it is not clear whether it is advancing or retreating. The interaction between these two major ecosystems is clearly dynamic.

Biotic assemblages

On top of the platform, the shallow impounded lagoon is divided into a mosaic of pools, around 20–30 cm deep at low tide, separated by ridges of sand, coral rubble and rhodoliths. There are seagrasses (*Thalassia hemprichii*) in the sand, tufted *Sargassum* and other leafy algae on coral stones and rubble, patches of rhodoliths and a variety of scleractinian corals. Live coral cover may be as high as 30%. The corals are moderately diverse with mainly small colonies of *Acropora*, *Merulina*, *Galaxia*, *Seriatopora*, *Pocillopora*, *Fungia*, a lobate *Porites* and a variety of faviids and mussids. Rubble and sand derived from these corals and the rhodoliths is clearly in-filling the pools. In some places these sediments and *in situ* coral skeletons have consolidated and formed a new rock platform surface. In such places *Porites* micro-atolls grow and are an important part of the in-fill process (Fig. 11). There are

also some sandy cays on the platform, inhabited by burrowing crabs and molluscs that are characteristic of the upper-littoral zone.

The steep outer ramp has very few corals – live coral cover being less than 2%. The coral colonies present, mostly faviids, are invariably small and prostrate. Crustose and turf algae dominate the pavement of this zone. However, the lower reef flats at the base of the ramp are rich in corals with live coral cover as high as 90% (Figs 12 and 13). Several kinds of fleshy sponge are common among the corals of the lower flat. *Tridacna squamosa* is also common there. Other molluscs and invertebrates are rare. The corals in this lower-littoral zone are smothered, to greater or lesser extent, by mud but flourish none-the-less. Coral species diversity in this zone is high. A collection made from several localities has not yet been identified but was estimated to include at least sixty species. Massive faviids and mussids are most common but there is usually a narrow band of *Acropora* along the reef edge (Fig. 13). The fore-reef below the reef edge slopes steeply into the subtidal zone and, from what could be seen of it, is rich in foliose and other corals. Sea whips and sponges also feature strongly in the subtidal zone.

Nearby patch reefs in Talbot Bay

Landings were made on several small patch reefs:

- south of Mangrove Island (Transect 4);
- in the channel of the NW corner of Molema Island (Transect 6);
- in the channel SE of South Turtle Reef.



Figure 12. Edge of a small patch reef south of Mangrove Islands (Molema Island in the background) at extreme low tide showing a species-rich coral assemblage, mainly massive faviids and mussids with an *Acropora* sp. fringe [Photo: S Blake, WAMSI].



Figure 13. Edge of a narrow fringing reef on a small island bordering the main navigation channel southwest of Molema Island at extreme low tide showing the *Acropora* sp. fringe [Photo: S Blake, WAMSI].

These reefs are all less than 100 m in diameter, flat and exposed only briefly at extreme low tide. They are all heavily affected with mud but support profuse growth of live corals. The coral assemblages appear to be the same as those on the lower reef-front flats of Turtle Reef with massive faviids and mussels behind a narrow band of *Acropora* at the edge, and rich growth of foliose corals, sea whips and sponges on the vertical, subtidal fore-reef walls. At the centres of the larger of these patch reefs, there are unusual accumulations of *Acropora* and other coral rubble in a mushy mud matrix. Soundings around these reefs found precipitous drop-offs to at least 30 m indicating that the coral growth is atop cliffed pinnacles or ridges, presumed to be high points of submerged terrestrial landforms.

Discussion

The prolific growth and species-richness of coral in these mud-dominated conditions is noteworthy. Further study is needed to identify the species present, to assess their assemblages and compare them with lagoonal and reef-front assemblages of fringing reefs around the islands of the Buccaneer Archipelago in more open sea conditions.

Coral growth at Turtle Reef is prolific in three zones:

- the high, upper-littoral lagoon impounded by algal terraces and rhodolith banks;

- the lower-littoral, reef-front flats (below the ramp) at extreme low tide level;
- the steep to vertical subtidal fore-reef walls.

There is very little coral growth on the reef-front ramp and in this respect Turtle Reef is unlike the fringing reefs of the North Kimberley, but resembles Montgomery Reef. The reef-front ramp is analogous to the 'algal cap' noted on the rim of many platform reefs, however we believe that its thickness on Turtle Reef may be an order of magnitude greater than algal caps observed in meso to microtidal conditions, due to the extreme tidal range in the Kimberley.

Crustose algae and algal rhodoliths play an important role in the construction of terraces and banks at the top of the ramp that impound shallow water over the vast reef platform in the middle/upper-upper littoral zone. Biogenic carbonate production by corals and calcareous algae in the lagoon is active. Corals are the principal producers of carbonate on the lower littoral flats and fore-reef slopes, supplemented by carbonate sediment delivered by water flow from the lagoon, and there is outward reef growth.

There is a dynamic, inter-active relationship within Talbot Bay between the massive mud banks and coral reefs. Both the deposition of mud and the connectivity and recruitment of coral communities, and the complex spatial distribution of these habitats, must be determined by the complexities of tidal currents. As far as these

authors are aware, such a situation has never been described and would be a worthy subject for future study.

The high, massive platform with its impounded lagoon and very steep, convex and barren ramp are unusual features. Rather than wave exposure, it appears that a complex interaction between ebb and flood tidal currents is responsible for the reef's large-scale morphology. There are many similarities in these regards to Montgomery Reef. Further survey is needed to determine whether reef structures of this kind are more widely distributed in the Buccaneer Archipelago.

The geology and origins of the Turtle Reef platform (and others in Talbot Bay) remain unknown. Assuming the basal (Pleistocene and older) rock is sedimentary, key questions are what kind of sediment is it, what are its origins and what is its age. The platform might be:

- Of Holocene age, constructed entirely of marine biogenic carbonate. If that were the case, very rapid and voluminous carbonate production would be indicated.
- A pre-existing marine biogenic structure, built prior to the last transgression, with a veneer of modern reef growth. In this case it might be of Pleistocene age and the first example of an onshore Kimberley reef built in that period. Interpretation of these massive reefs in this way would need to take account of Neogene-recent subsidence.
- A pre-existing structure that is not of marine biogenic origin. It could comprise Tertiary to Pleistocene clastic alluvial and colluvial terrestrial sediments deposited in the valley floors between the folded ridges of the peninsular, its surface populated by reef building corals and algae, with marine sedimentary processes following subsidence and inundation by the post-glacial transgression.

This matter can be resolved only by drilling. Whatever the origins and age of the Turtle Reef platform, and of others like it in the vicinity, a carbonate structure of this scale supporting modern biogenic growth in a land-locked, macro-tidal, mud-dominated embayment is a highly unusual if not unique feature of the Kimberley. Both the geology and the contemporary biology of these reefs are worthy of intensive study.

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Appendix – Reef transects

The following field notes were made on site. Photographs taken at 1 m intervals along the transect tapes and voucher specimens of invertebrates are to be lodged with at the Western Australian Museum for future analysis and reference.

Transect 1 – 7 September 2010

South Turtle Reef (south of Molema Island) southern margin of reef (Figs 5a–c)

Start point (0 m): 16°17.667' S; 123°54.156' E. (Position on the lower part of the ramp; tide not low enough to see the reef edge.)

Finish point (120 m): 16°17.605'S; 123°54.141'E. (Position in the high lagoon).

Ramp steep, about 10°, with small, irregular ridges of crustose alga, very low algal turf and rhodoliths in shallow pools. Coral diversity and abundance very low; small, prostrate colonies only, mostly faviids. Small *Tridacna maxima* common. Change of slope at 35 m with a bank of rhodoliths about 12 m wide; then a pool (c. 30 cm deep) before a second, slightly higher rhodolith bank at 60 m and behind that the shallow lagoon on the top of the platform, estimated at about 5 m above low tide level.

Pool in between the rhodolith banks with abundant rhodoliths, some coarse sand and rubble, abundant fungiids and some other corals, and a few small patches of *Thalassia*.

The upper lagoon 10–50 cm deep, with sand and rubble, patches of *Thalassia* and leafy macro-algae; about 20% live coral cover, mostly faviids but a moderate diversity. Low diversity of associated invertebrate fauna. Gastropods: *Tectus pyramis*, *Trochus fenestrata*, *Astraliium rotularia*, *Angaria delphinus*, *Pseudovertagus aluco*, *Drupella rugosa*; *Melo amphora*; bivalves: *Fragum unedo*, *Tellina staurella*. These are typical of intertidal reef assemblages in the Kimberley Bioregion.

Transect 2 – 8 September 2010

South Turtle Reef (northern side of reef)

Start point (0 m): 16°16.746'S, 123°54.332'E (16:38)

Finish point (60 m): 16°16.777'S, 123°54.337'E

Transect began on a low flat, about 30 m wide, just emergent at low tide, muddy but rich in live corals, with an *Acropora* fringe and diverse massives behind, mainly faviids. Live coral cover estimated at c. 80%.

Ramp very steep, c. 15°, convex, no distinct crest but "rolls over" a rhodolith bank with the high lagoon behind. Height of the platform estimated at about 4.5 m above water level at low tide. Pavement of ridged crustose algae and very low algal turf; very few corals, all tiny, mainly prostrate faviids and *Porites*. *Angaria delphinus*, *Astraliium rotularia* the only common molluscs.

Lagoon with rhodoliths and abundant and diverse corals (70–90% live cover) including *Acropora* and branching *Porites* close to the rhodolith bank. Further back with more sand *Thalassia* and leafy algae. Large *Tridacna squamosa* common; *Hippopus hippopus* present also. Few other molluscs.

Transect 3 – 9 September 2010

South Turtle Reef (northern side of the reef. Figures 6a–c)

Start point (0 m): 16°16.675'S, 123°54.064'E

Finish point (180 m): 16°16.697'S, 123°53.927'E

At this site there was a lower-littoral flat between the reef edge and the base of the ramp, approx. 100 m wide, with an elongate deep hole at its centre. The ramp was very steep (around 25° at the base) and convex, without a distinct crest but marked at the top by a rhodolith bank about 30 m wide, containing a shallow lagoon on the upper platform, perched a meter at least above the water level of the channel. The platform above the ramp was estimated to be about 4.5 m above the low tide water level.

The lower flat had live coral cover of about 90% along the reef-

front margin, with an *Acropora* fringe and mainly massives behind but with diverse other corals including three species of fungiid and several kinds of sponge. The pavement between the corals was mud and coral rubble. Coral growth around the rim of the deep pool was particularly vigorous, like that of the reef-front, and its sides bore total cover of foliose corals.

There was a low (c. 10 cm) sharp-edged escarpment along the base of the ramp, a fan of white sand and a band of rubble and old tridacna shells. The pavement on the ramp was of ridged crustose algae with a sparse, low algal turf. Live coral cover was sparse (< 2%) comprising very small prostrate forms. At the back of the crest the ramp merged into the lagoon. In this zone there was a diverse coral assemblage with about 10% live cover. The lagoon was 20–40 cm deep with a sand/rubble floor and *Thalassia*, tufted leafy macro-algae, rhodoliths and patches of diverse massive and branching corals with live cover estimated at 15–20%. *Tridacna squamosa* was common but there were few *Hippopus hippopus*. No holothurians or other echinoderms were seen. This habitat appeared to cover much of the high platform.

Transect 4 – 10 September, 2010

Southern margin of Mangrove Island.

Three short parallel transects were made across the reef-front.

4 a) *Start point* (0 m): 16°13.472'S, 123°51.881'E
Finish point (30 m): 16°13.456'S, 123°51.879'E

4 b) *Start point* (0 m): 16°13.476'S, 123°51.872'E
Finish point (30 m): 16°13.461'S, 123°51.866'E

4 c) *Start point* (0 m): 16°13.480'S, 123°51.864'E
Finish point (30 m): 16°13.448'S, 123°51.856'E

This is a low reef sloping up to a mud bank in front of the mangrove fringe. The reef-front slope, exposed at extreme low tide, was muddy but carried a diverse coral assemblage with an *Acropora* fringe in front of a 20 m wide band of massive, foliose and encrusting corals. Other invertebrates sparse, the most obvious being a few very large *Tridacna squamosa*.

Transect 5, 12 September, 2010

Western margin of North Turtle Reef, south of large drainage channel.

Start point (0 m): 16°14.467 'S, 123°54.739 'E. (Position at reef edge of lower reef flat.)

Finish point (256 m): 16°14.602 'S, 123°54.721 'E. (Position in high lagoon.)

The reef edge was just exposed at low tide (0.7 m). Rich growth of foliose corals, sponges, sea whips on the vertical fore-reef wall. Reef-front muddy; est. 20% live coral; no *Acropora* bank but clusters of those species along the margin; Band about 10 m wide along the margin of diverse coral assemblages, mostly faviids and encrusting species – no field of massive domes. About 50 m from the reef edge to the base of the ramp – rear part muddy rubble with *Halophila* and *Caulerpa* and abundant fungiids – *Cycloseris*, *Fungia* and (?) *Herpolitha*.

Ramp solid, about 35 m wide, c. 10° slope, elevation estimated at about 5 m above the water level at the reef edge; with crustose algal surface and low algal turf; many small ridges forming mini-terraces on the slope. Corals sparse, colonies small and prostrate, < 5% cover, mostly faviids and *Porites*. Only common molluscs *Angaria delphinus* and *Tectus pyramis*.

Ramp levelled out at the crest to a higher flat; some shallow pools with faviids, *Pocillopora*, *Galaxia*; also *Tridacna squamosa* and *Hippopus hippopus*.

At 165–180 m there was a ridge or second crest with a narrow sand fan along its lower edge; its surface rough, crustose algal pavement with low algal turf and meandering algal terraces, few rhodoliths. Many shallow (c. 10 cm) pools, sandy with rubble and leafy macro-algae, some *Thalassia* and *Caulerpa*, grey and green flabellate sponges, some patches of rhodoliths; scleractinian corals sparse. Off the transect line to the east, along the side of a major drainage channel, the pools became crescentic with abundant rhodoliths – presumably the result of strong run-off tidal currents.

At 210–256 m (end of transect) the platform became a flat pavement with low algal turf and dead coral slabs; areas of shallow, sandy pools (< 10 cm) with *Thalassia* (sometimes in patches with 10–30% cover), scattered rhodoliths and sparse corals, mainly small faviids, *Galaxia* and *Porites* micro-atolls; dead coral slabs heavily bored by the lithophagids (*Lithophagateres* and *Botula fusca*) some higher rocks with rock-oysters, chitons and barnacles indicating a position at the base of the upper-littoral zone. This seemed to be the condition of the reef platform beyond the end of the transect to the south.

Transect 6

Small patch reef in channel, NW end of South Turtle Reef;

Start (0 m): 16°14.886'S, 123°51.948'E

Finish (44 m): 16°14.903'S, 123°51.931'E

This was one of two small patch reefs in the channel; each about 100 m diam.; exposed at 0.7 m tide. Horizontal, entire surface covered with dense coral assemblage, c. 80% live coral cover with interspaces of mud and coral rubble. Dense *Acropora* bank around the reef-edge margin at water level; corals atop mainly massive faviid and mussid domes but with diverse other encrusting and foliose species and some soft corals. Very few other invertebrates – one green crinoid and one echinoid (*Phyllacanthus* sp.) seen under coral slabs. No tridacnids seen. A representative collection of corals was made at this site (see also Peter Strain's photographs numbers 1 – 17).

Patterns in marine community assemblages on continental margins: a faunal and floral synthesis from northern Western Australian atolls

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Abstract

Corals and fishes are the most visually apparent fauna on coral reefs and the most often monitored groups to detect change. In comparison, data on noncoral benthic invertebrates and marine plants is sparse. Whether patterns in diversity and distribution for other taxonomic groups align with those detected in corals and fishes is largely unknown. Four shelf-edge atolls in the Kimberley region of Western Australia were surveyed for marine plants, sponges, scleractinian corals, crustaceans, molluscs, echinoderms and fishes in 2006, with a consequent 1521 species reported. Here, we provide the first community level assessment of the biodiversity of these atolls based on these taxonomic groups. Four habitats were surveyed and each was found to have a characteristic community assemblage. Different species assemblages were found among atolls and within each habitat, particularly in the lagoon and reef flat environments. In some habitats we found the common taxa groups (fishes and corals) provide adequate information for community assemblages, but in other cases, for example in the intertidal reef flats, these commonly targeted groups are far less useful in reflecting overall community patterns.

Keywords: biodiversity, marine communities, species turnover, Mermaid Reef, Rowley Shoals, Scott Reef, Seringapatam Reef

Introduction

Describing patterns of species diversity and distribution is important for detecting changes to community assemblages; yet marine community assemblage data are rare. Studies on coral reefs have tended to focus on corals and fishes, and less on noncoral benthic invertebrates (Przeslawski *et al.* 2008). While corals and fishes can be the most visually apparent faunal taxa on tropical reefs, there is significantly less information available on other taxonomic groups, even though they may be providing crucial ecosystem services, including nutrient cycling, water quality maintenance and herbivory (Przeslawski *et al.* 2008).

Most of our knowledge about the diversity, distribution and ecosystem function of tropical ecosystems is based on corals and fishes (Przeslawski *et al.* 2008). Some authors question whether diversity patterns derived from well known taxa can be used to describe whole community patterns (Purvis & Hector 2000). Moreover, in the majority of marine and terrestrial communities most species occur in relatively low abundance (Gray *et al.* 2005), but much of the literature on the contribution of biodiversity to ecosystem function is based on common species (Lyons *et al.* 2005). However, if whole community data are available, the information on rare species and poorly studied taxa could be used to test whether patterns in diversity, distribution and abundance suggested by the more common species

reflect overall community patterns (Ferrier & Guisan 2006).

Comparative quantitative baseline data that can be used to detect change are particularly important in the context of global climate change (Przeslawski *et al.* 2008). The diversity-stability hypothesis suggests that biodiverse systems provide a buffer against major changes in an ecosystem in response to environmental change (Chapin III *et al.* 2000). This suggestion highlights the need to assess community diversity for general patterns, where community data are available.

Spatial heterogeneity in species richness and composition is an obvious feature of the natural world (Gaston 2000). Along the northern Western Australian coast species richness and composition may vary with latitude (fishes, Hutchins 2001; Travers *et al.* 2006) and can also vary with habitat (sponges and fishes, Fromont *et al.* 2006; Travers *et al.* 2006). A gradient in species composition and diversity has been discussed for northern Western Australia with high diversity of tropical species in lower latitudes near the coral triangle and decreasing southward (Wilson & Allen 1987; Wells & Allen 2005). To date these findings have been restricted to certain better known taxonomic groups such as corals (Veron & Marsh 1988; Veron 1993; Greenstein & Pandolfi 2008), echinoderms (Marsh & Marshall 1983), molluscs (Wells 1986, 1990) and fishes (Allen 1997; Hutchins 1999).

The atolls of the Sahul Shelf in northern Western Australia are emergent oceanic reef systems at the edge of the Australian continental shelf (Fig. 1), Mermaid, Scott (South and North), and Seringapatam Reefs are four

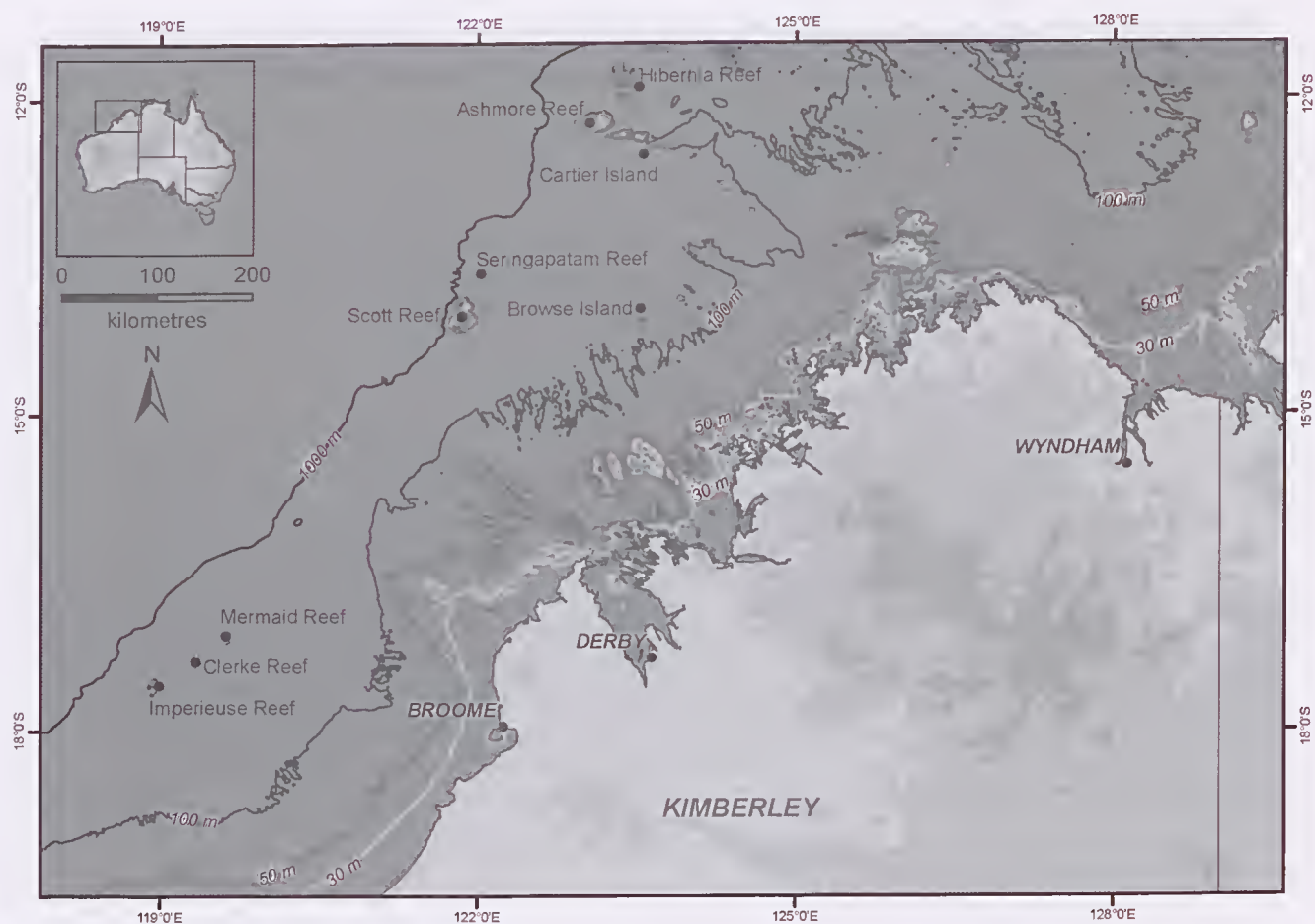


Figure 1. Map of northern Western Australian atolls.

of these. These atolls are thought to have formed some 5–6 million years ago (Anon 2008). The waters in and around the atolls are typical of the Timor Sea and the north eastern Indian Ocean, being warm, clear and oligotrophic. Surface currents in some channels within the atolls can reach up to 2 knots during spring tides. At 9 metres depth at South Scott Reef the mean water temperature range is 25–31 °C (Gilmour *et al.* 2009). These atolls occur in one of the most cyclone-prone regions in the world; in 2004 a category 5 cyclone passed directly over South Scott and North Scott Reefs (Gilmour *et al.* 2009). The intensity of storm events is predicted to increase with global climate change (Solomon *et al.* 2007) and consequent damage will depend on the wind speed, and the direction and duration of the event (Puotinen 2007). There is currently little knowledge of how an increase in the occurrence of extreme events will affect tropical benthic invertebrates, or how community assemblages may change as a consequence (Przeslawski *et al.* 2008).

Realising conservation goals requires strategies for managing entire systems, including areas identified as important to both production and protection (Margules & Pressey 2000). Three of the atolls (South Scott, North Scott and Seringapatam Reefs) discussed in this paper are presently unprotected and subject to fishing pressure and increased shipping, which may introduce non-native species.

The study atolls have been the subject of previous investigations. In 1982 and 1984 the Western Australian Museum undertook species inventories of taxonomic groups including molluscs, corals, echinoderms and fishes at Mermaid, Clerke, South Scott, North Scott, and Seringapatam Reefs (Berry 1986). The three northern atolls, South Scott, North Scott, and Seringapatam Reefs, have been the subject of intensive recent study as a result of the presence of a major gas reserve beneath and adjacent to them. Heyward *et al.* (2007) established baseline monitoring of fishes and corals, while Smith *et al.* (2008) examined coral mortality and recovery after a mass bleaching event that affected the atolls in 1998. Underwood *et al.* (2007) examined genetic connectivity in a brooding coral species, *Seriatopora hystrix*, in part to establish the role of dispersal in maintaining populations at these atolls.

In 2006 the Western Australian Museum surveyed four of these atolls (Mermaid, South Scott, North Scott, and Seringapatam Reefs) and the diversity and distributions of seven taxa were documented (Bryce 2009 and papers therein). Results were presented for each taxonomic group, with varying levels of analyses, and there was no synthesis of results across all taxa. For a number of taxa it was observed that there were differences in species richness and composition within the different habitats and atolls. A number of factors were discussed as potentially affecting assemblage

patterns between atoll and habitat, including atoll separation distance, habitat, and exposure but none of these were specifically analysed.

Here, we present a community-level analysis of the biodiversity of these atolls using the 2006 survey data. This is the first assessment to be undertaken on the combined marine flora and fauna of the atolls in this region and the results will thus contribute to a greater understanding of current species richness (diversity) patterns, and community assemblage structure of these atolls. As very little is known about the factors that influence the distribution of these community assemblages, our analyses focused on exploring whether communities differed in terms of diversity and composition among the atolls and the habitats represented. We also assessed the potential role of abiotic environmental factors on community structure and explored the possibility that the distributions of the various taxa comprising the communities were correlated.

Methods

Field collection

During the 2006 survey a total of 45 stations were sampled encompassing four main habitat types (reef flat, tidal channel, reef front and lagoon; Table 1). The reef flat habitat was in the intertidal zone, whereas the other three habitats were subtidal. The tidal channel habitat was only present at Mermaid and North Scott Reefs. The stations sampled encompassed a range of substrates (rock, rubble and sand), exposures (e.g. to desiccation i.e. intertidal vs. subtidal, and exposed vs. protected from prevailing currents and cyclones), depths (0 to 20 m), and atoll separation distances (35 to 500 km).

Seven taxonomic groups were surveyed: marine plants (algae and seagrasses, Huisman *et al.* 2009), sponges (Fromont & Vanderklift 2009), corals (McKinney 2009), macromolluscs (≥ 10 mm, Bryce & Whisson 2009), crustaceans (decapods and stomatopods only, Titelius *et al.* 2009), echinoderms (except crinoids, Bryce & Marsh 2009) and fishes (Moore & Morrison 2009). Methodology varied among taxonomic groups and differed in some

habitats, with full details provided in Bryce (2009), and papers within. Briefly, marine plants and crustaceans were recorded as presence-absence, sponges, corals, molluscs and echinoderms were counted, and fish numbers were recorded on a semi-quantitative log abundance scale (Moore & Morrison 2009). The sampling effort within taxa for each station within a habitat was generally comparable. The intertidal reef flat was sampled as reef walks (rotenone stations in rock pools for fishes) and the area was searched for each taxa to generate a qualitative species list for all groups except sponges, which were always sampled quantitatively along transects. The reef flat station at Mermaid Reef was covered with flowing water so no rotenone station was surveyed for fishes. Instead fishes were surveyed by snorkel (Table 1) towards the reef front, so they were in a subtidal habitat different from the remaining taxa, which were sampled intertidally. The reef front and lagoon stations were all sampled using quantitative methods along transects (either tape or compass bearing) on SCUBA with comparable effort except for one lagoon station at Mermaid Reef, which was surveyed on snorkel, and a lagoon station at Seringapatam Reef, which was sampled qualitatively (Table 1). The tidal channel stations were qualitatively sampled on drift dives (Table 1). The lagoon and reef front subtidal habitats were videoed and analysed for percent cover at the quantitatively sampled stations (Morrison 2009).

Data analyses

Data analyses were based on a matrix of 1521 marine floral and faunal species from 45 stations. All analyses were undertaken in PRIMER v6.1.11 (Clarke & Warwick 2001; Clarke & Gorley 2006). Although, as mentioned previously, a few stations had non standard effort, this did not greatly affect the overall patterns in community structure and the relationships found among habitats and atolls. Data was examined for each taxonomic group (both abundance and presence-absence) in various combinations, i.e. motile vs. sessile vs. fishes, and with and without outliers to examine station groupings. The Mermaid reef flat station was removed from any further analysis as the community sampled at this station was not comparable, with fish surveyed on snorkel in a different depth to the remaining taxa (Table 1).

Table 1

Summary of the sampling methods and number of stations for each habitat and atoll. The same method was used for all stations within a habitat except where indicated by superscript. Sponges were sampled quantitatively along transects¹, Fish were sampled on snorkel^f, one station was sampled qualitatively².

	Habitat				Total
	Reef Flat	TidalChannel	Reef Front	Lagoon	
Method	reef walk, rotenone	drift dive	SCUBA Transects	SCUBA Transects	
Data	qualitative ¹	qualitative	quantitative	quantitative	
Atoll					
Mermaid Reef	1 ^f	2	5	8 ²	16
South Scott Reef	3	–	6	5	14
North Scott Reef	3	1	3	3	10
Seringapatam Reef	1	–	2	2 ²	5
Habitat Total	8	3	16	18	45

The overall structure in the community was explored using non-metric multidimensional scaling (nMDS) and cluster analysis using complete linkage, based on a Bray-Curtis dissimilarity matrix of presence-absence data. Presence-absence data was used to standardise the varying methods of quantification (presence-absence, counts, log-abundance) that were applied across the taxonomic groups. The similarity profiles (SIMPROF) test (Clarke *et al.* 2008) was used to determine if there was significant structure in the observed station groupings in the nMDS and cluster analyses. These analyses were done firstly on all stations (except the reef flat station at Mermaid Reef) to explore the broad groupings for the four main habitat types, and secondly on a subset of the data from the subtidal quantitative stations, to examine the lagoon and reef front communities in more detail. Analysis of similarity (ANOSIM) was used to test for differences in the community due to atoll and habitat. We did this firstly, with habitat nested in atoll as the tidal channel habitat was not sampled at all atolls and the reef flat data at Mermaid Reef was not analysed, and secondly as a crossed test of atoll and habitat for the lagoon and reef front communities.

Similarity percentages (SIMPER) were used to identify species that were consistently present in a habitat or atoll (typifying species), and those that discriminated between habitats or atolls, that is consistently present in one habitat or atoll but absent from others (discriminating species). Typifying species had a high average presence across stations within a habitat or atoll and a high similarity to SD ratio of approximately one. Discriminating species were those that had a higher average presence (~1) in one habitat or atoll and a high dissimilarity/SD ratio (~1). These analyses were undertaken firstly on the entire dataset to look for typifying and discriminating species for each habitat, and then repeated for the quantitative subtidal stations in the lagoon and reef front habitats to determine typifying and discriminating species for each atoll in these habitats only.

To explore whether the structure in the biotic communities could be explained by abiotic environmental variables, the stations were coded for a range of physical factors that could have an influence on the biological communities. Due to the variation in methods among habitats, these analyses were only undertaken on the communities at the quantitative subtidal stations (lagoon and reef front, Table 1). Seven abiotic environmental variables were used: percent rock, percent rubble, percent sand, geomorphic zone (1: lagoon, 2: reef front), direction quadrant, depth, and atoll separation distance. Percent rock, rubble, and sand were calculated from the video transects at each station (values used were an average of the replicate transects per station) and were examined because species are usually associated with different substrates. A measure of exposure to prevailing winds and currents was estimated (direction quadrant) by placing a compass rose on the map of each atoll and coding the stations for the exposure quadrant they occurred in (1: NNE, 2: NE, 3: SE, 4: SSE, 5: SSW, 6: SW, 7: NW, 8: NNW). The maximum depth recorded from each station was used. The atolls in this study were varying distances apart, which has implications for population connectivity between atolls.

Atoll separation distance is the approximate distance in kilometres of each atoll from the northernmost atoll (Seringapatam – 0, North Scott – 35, South Scott – 55, Mermaid – 500). This abiotic dataset was normalised and nMDS and cluster analyses were performed using Euclidean distance. The BEST procedure was employed as a global test to determine if there was biotic structure that could be explained with the abiotic variables, and this was further explored using the LINKTREE analysis (Clarke & Gorley 2006; Clarke *et al.* 2008) to identify which factors may have influenced biota.

Finally, we used a 2nd stage MDS to correlate the resemblance matrixes for each taxonomic assemblage, to determine how similar their multivariate pattern was, and if each taxonomic group provided the same information about the interrelationships of atolls and habitats.

Results

Patterns in species richness among habitats and atolls

The intertidal reef flat communities had lower species richness (mean across all atolls of 181.5 species) than the subtidal habitats of tidal channel ($\bar{x}$ = 268), reef front ($\bar{x}$ = 548.5) and lagoon ($\bar{x}$ = 530). South Scott consistently had highest species richness of the atolls sampled in all habitats and Seringapatam had lowest species richness, but this atoll also had the lowest sampling effort.

Mean species diversity varied for each taxonomic group and no general trends were apparent. For example, mean species richness of molluscs was highest at South Scott Reef on the reef flat, Mermaid Reef in the tidal channel, and North Scott Reef on the reef front, whereas fishes had highest species richness at South Scott Reef on the reef front and lagoon, and North Scott Reef and Seringapatam on the reef front (Fig. 2).

All taxonomic groups were found in all habitats but their proportional contribution to species richness within habitats differed. Species richness in the reef flat habitat was dominated by molluscs, fishes dominated in tidal channels and on reef fronts and corals had high species richness on reef fronts and in lagoons. The remaining taxa, marine plants, sponges, crustaceans and echinoderms, had lower species richness than the other groups, but their mean species richness was similar across all habitats (Fig. 2). The unusually high coral diversity on the reef flat at Mermaid Reef was partly due to only one station being sampled and the different sampling effort that was applied at this station (qualitative rather than quantitative). Species richness of the subtidal habitats (lagoon, reef front and tidal channel) was dominated by corals and fishes (Fig. 2).

Differences in the floral and faunal communities among habitats

The intertidal reef flat community significantly differed from the communities at the three subtidal habitats (Fig. 3). Within each habitat group there was clear structuring due to atolls, with Mermaid Reef separating from the northern atolls of Scott (North and South) and Seringapatam Reefs (Fig. 3). The SIMPROF

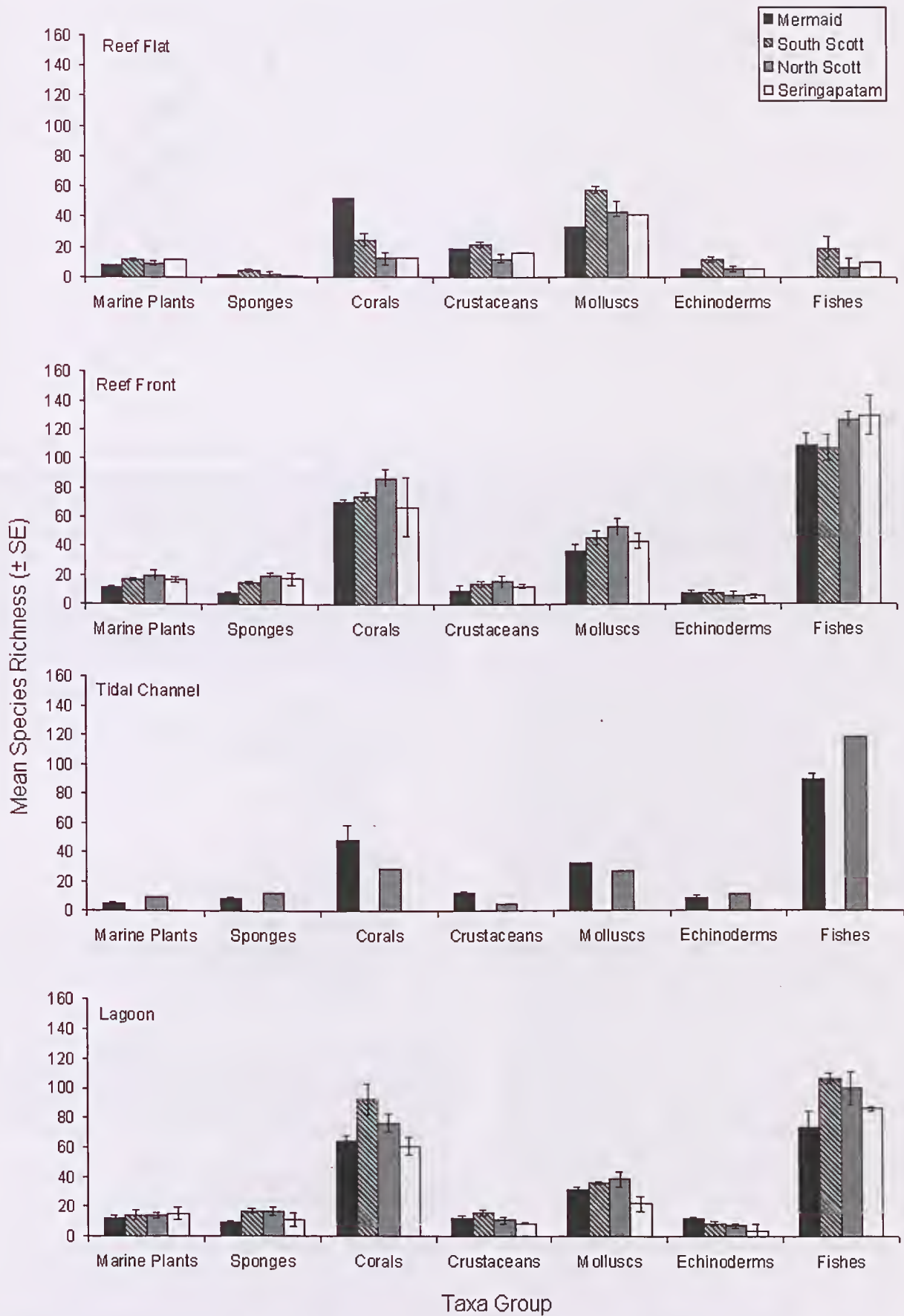


Figure 2. Mean species diversity ($\pm$ SE) of each taxa group for each habitat and atoll. NB. Tidal channel habitat was not present at South Scott or Seringapatam Reefs and no fishes were surveyed on the reef flat at Mermaid Reef.

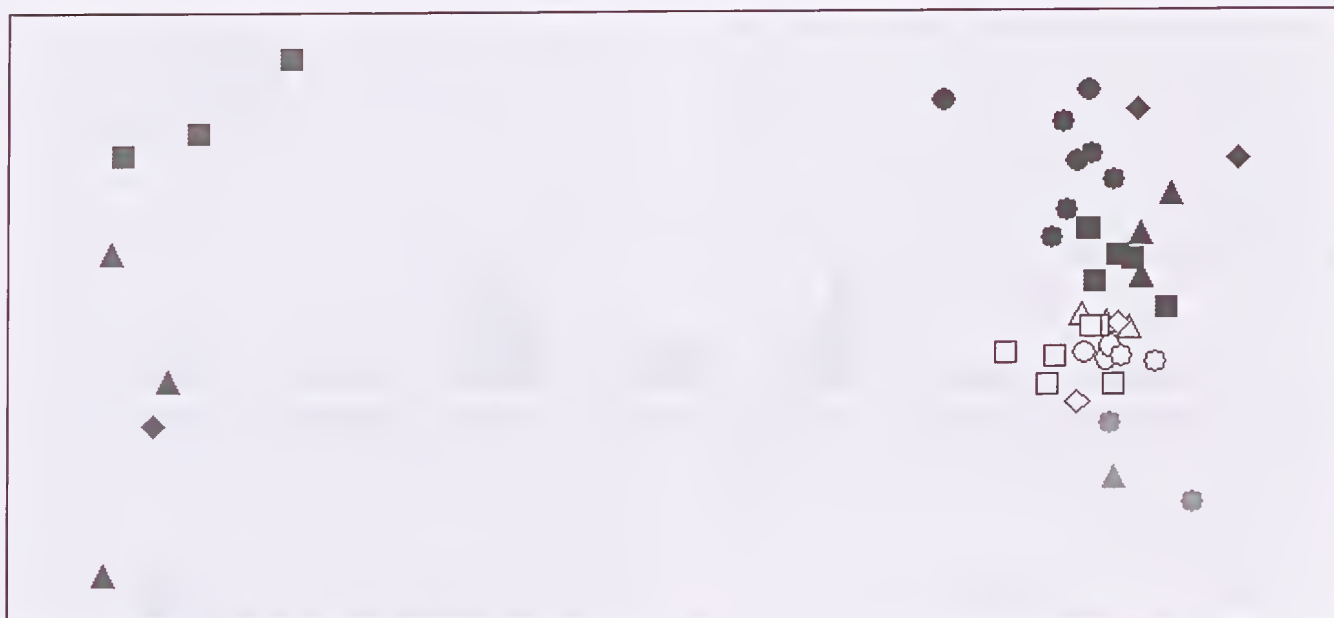


Figure 3. Non-metric multidimensional scaling plot of the marine floral and faunal communities of the North-West Shelf atolls for all habitats sampled. Habitats are distinguished by shading and the atolls are indicated by symbol shape. Habitat: Reef Flat (dark grey), Lagoon (black), Reef Front (white), and Tidal Channel (light grey). Atoll: Mermaid Reef (●), South Scott Reef (■), North Scott Reef (▲), and Seringapatam Reef (◆). Stress 0.08. The separation of subtidal habitats (lagoon, reef front and tidal channel), from the intertidal reef flat was significant (SIMPROF $p < 0.05$, Bray-Curtis Similarity, 15%)

and ANOSIM ($R = 0.8$, $p < 0.001$) tests showed significant structure in the faunal and floral communities of these atolls and habitats.

Average similarity of the reef flat communities was low (30%; Table 2) and this was clearly visible on the nMDS plot where the stations were widely separated (Fig. 3). Seven species typified the reef flat habitat, *Tridacna crocea*, *Lambis chiragra*, *Conus miliaris*, *Cypraea moneta*, *Acropora digitifera*, *Boodlea vanbosseae* and *Turbinaria ornata* (Appendix Table A1). The community on the reef flat was very different from all other habitats with high dissimilarity (~90%; Table 2). *Boodlea vanbosseae* and *Cypraea moneta* were key discriminating species distinguishing this habitat from all other habitats (Table A1).

The communities on the reef fronts were most similar (similarity 50%; Table 2) and the communities in tidal channel habitats the least similar (37%; Table 2). The tidal channel community was most similar to the reef front community (dissimilarity of tidal channel vs. reef front = 61%; Table 2) compared to the lagoon community (dissimilarity tidal channel vs. lagoon = 73%; Table 2) and these patterns were clearly visible on the nMDS plot (Fig. 3). Forty four species typified the tidal channel and many of these were absent from the reef flat habitat (Table A1). Only two fish species consistently discriminated the tidal channel from all other habitats, Diana's Pigfish, *Bodianus diana* and the Emperor Angelfish, *Pomacanthus imperator* (Table A1).

The reef front community had 58 species that typified this habitat (Table A1) but no discriminating species that characterised it. However, eight species were more typical of the reef front than the lagoon. These were *Porites vaughani*, *Cerithium echinatum*, *Cephalopholis urodeta*, *Chaetodon punctatofasciatus*, *Chronis xanthura*, *Forcipiger flavissimus*, *Naso caesi*, and *Thalassoma*

Table 2

Average Bray-Curtis similarity of the community within each habitat (a) and the dissimilarity between habitats (b) based on the SIMPER analysis. High % indicated greater similarity or dissimilarity.

Habitat	%
a) Average similarity	
Reef Flat	30
Tidal Channel	37
Lagoon	40
Reef Front	50
b) Average dissimilarity	
Reef Flat vs Tidal Channel	89
Reef Flat vs Reef Front	86
Reef Flat vs Lagoon	87
Lagoon vs Reef Front	65
Lagoon vs Tidal Channel	73
Reef Front vs Tidal Channel	61

quinquevittatum (Table A1). Only nine species typified lagoons and three of these species consistently discriminated this habitat from all other habitats: the coral, *Acropora abrolhosensis*, and two damselfishes, *Pomacentrus moluccensis* and *Dascyllus aruanus* (Table A1).

Community turnover between atolls for the subtidal habitats of lagoon and reef front

There was significant structure in the subtidal communities of the lagoon and reef front habitats (SIMPROF, Fig. 4), and these communities were significantly different between atolls (ANOSIM $R = 0.7$, $p < 0.001$) and habitats ($R = 0.86$, $p < 0.001$). The community at Mermaid Reef was significantly different from the other atolls ($R = 0.85 - 0.95$, $p < 0.05$). South Scott and North Scott Reefs were significantly different from each

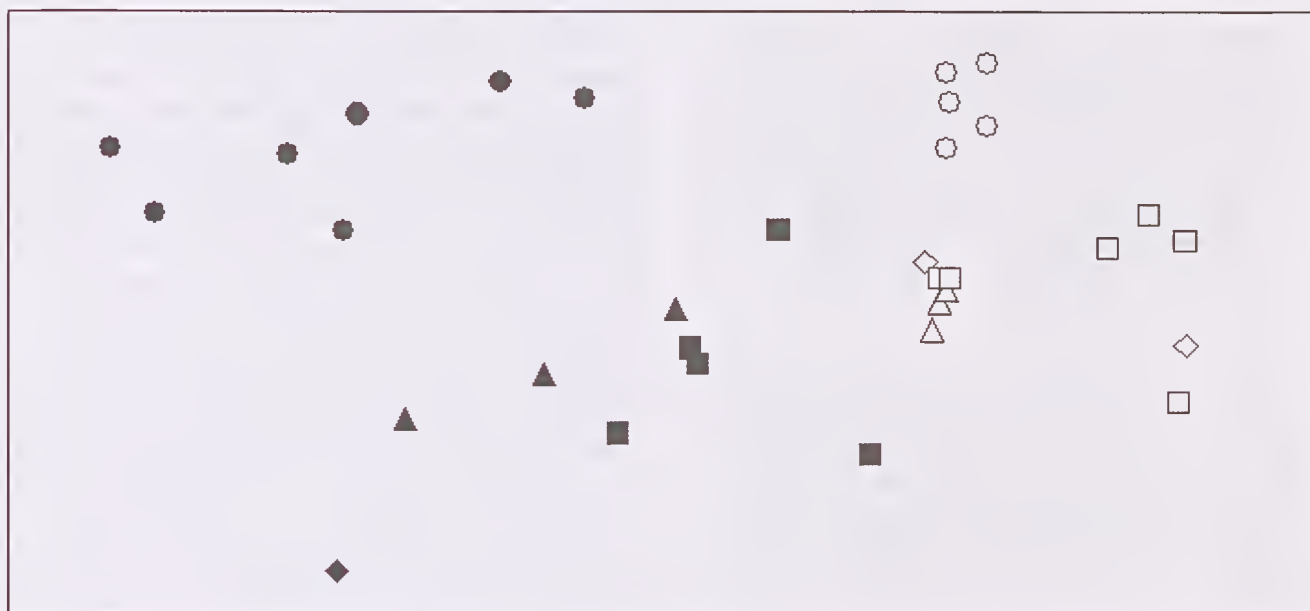


Figure 4. Non-metric multidimensional scaling plot of the marine floral and faunal communities in the lagoon and on the reef front. Symbols as in Figure 3. Stress 0.11.

other ($R = 0.34$, $p < 0.05$), but had a low R value indicating low difference and the significance p value is likely related to the larger number of replicates at these two reefs compared to Seringapatam Reef which was similar to both North and South Scott Reefs with a non significant low R ($R = 0.4$, $p > 0.05$; Table 3, Fig. 4).

For each of these habitats the atolls had a similar average similarity, with the similarity of the reef front

habitat (52–59 %; Table 4) being slightly higher than the lagoon habitat (48–53 %; Table 4). The lagoon habitats were slightly more dissimilar than the reef front habitats for each atoll pair, indicating more unique floral and faunal components in the lagoons compared to the reef front habitats (Table 4). This is also evident on the nMDS plot, where the reef front stations are more tightly clustered than the lagoon stations (Fig. 3).

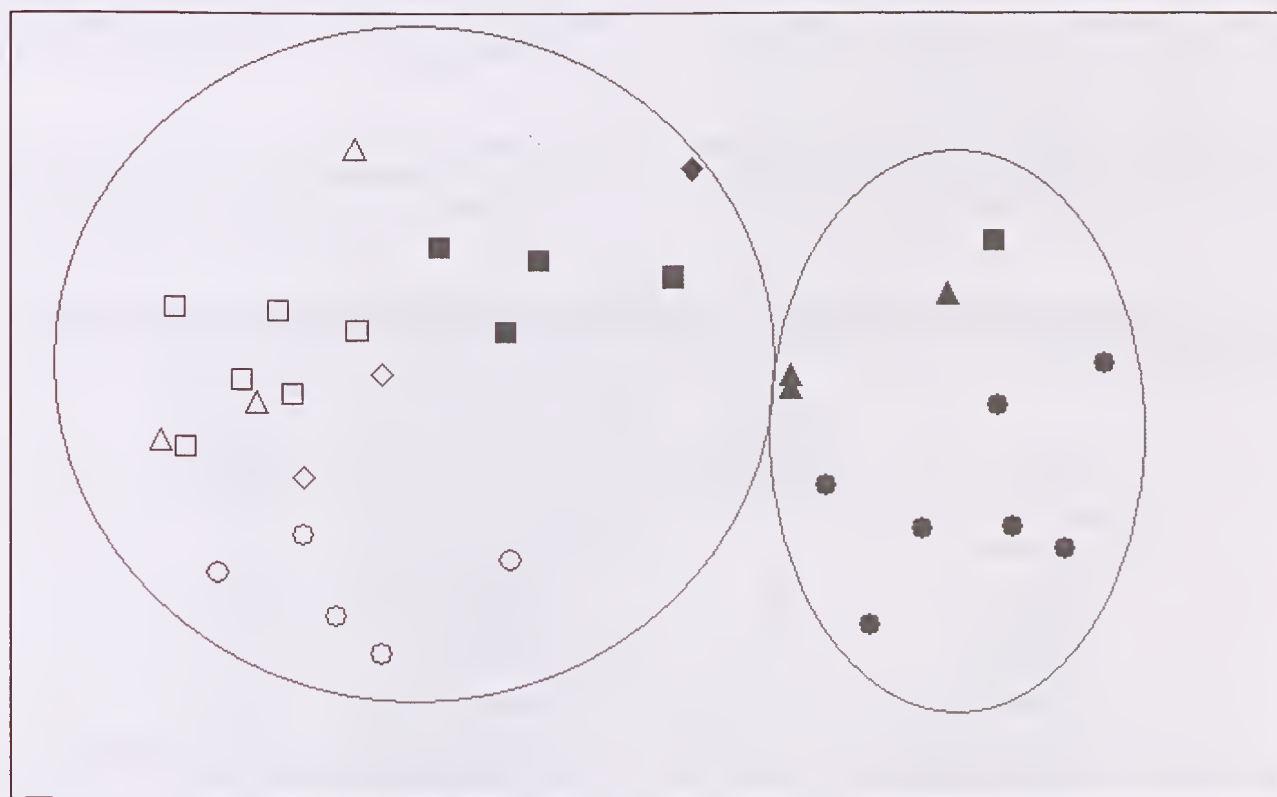


Figure 5. Non-metric multidimensional scaling plot of the abiotic environmental factors for the stations in the lagoons and on the reef front. Cluster groups are significant with SIMPROF, $p < 0.05$ and there was no significant grouping below this level. Symbols as in Figure 3. Stress 0.15.

Table 3

ANOSIM pairwise tests for differences between atolls for reef front and lagoon habitats, $p < 0.05$ is significant.

Atoll	R	p
Mermaid, South Scott	0.9	0.001
Mermaid, North Scott	0.9	0.001
Mermaid, Seringapatam	1	0.006
South Scott, North Scott	0.3	0.03
South Scott, Seringapatam	0.4	0.83
North Scott, Seringapatam	0.4	0.15

Species from all taxonomic groups discriminated between atolls in the lagoon habitat, but within the reef front habitat no echinoderm species discriminated atolls (Table A2, A3). There was a high degree of dissimilarity between atolls, with many species across the taxonomic groups only being recorded at one atoll within a habitat, and this was more apparent in the lagoons than on the reef front.

Overall, 17 species found in reef front habitats typified one of the atolls and discriminated that atoll from the other three (Table A2). For example, four species (*Morula uva*, *Chaetodon adiergastos*, *Chaetodon unimaculatus* and *Lutjanus rivulatus*) discriminated the reef fronts at Mermaid Reef from the reef fronts at all other atolls. Nine species discriminated North Scott from all other atolls (*Niplates* sp. NW4, *Acanthastrea brevis*, *Ctenactis echinata*, *Barbatia* aff. *coma*, *Chicoreus brunneus*, *Lioconcha castrensis*, *Pinna bicolor*, *Cheilodipterus quinquelineatus*, and *Pomacentrus amboinensis*). Four species discriminated Seringapatam from all other atolls (*Haloplegma duperreyi*, *Pterocladia caerulea*, *Halichoeres nebulosus*, and *Stethojulis bandanensis*), but no species typified South Scott, although there were species that separated South Scott from each of the other atolls.

In the lagoon, 54 species typified one atoll and discriminated that atoll from the other three atolls (Table A3). Two species discriminated Mermaid Reef from all other atolls (*Amblygobius phalaena* and *Centropyge eibli*).

Nine species distinguished the South Scott lagoon from all other atolls (*Ganonema farinosum*, *Echinopora horrida*, *Montastrea curta*, *Pocillopora verrucosa*, *Pilodius* sp. 1, *Trapezia septata*, *Acanthurus nigricans*, *Chromis xanthura*, and *Dascyllus trimaculatus*). Five species distinguished North Scott Reef from the other three atolls (*Avrainvillea amadelphe*, *Barbatia* aff. *coma*, *Cypraea erosa*, *Vasum turbinellum*, and *Pseudocheilinus octotaenia*), while 38 species distinguished Seringapatam Reef from all other atolls (*Amphiroa fragilissima*, *Rhipilia crassa*, *Rhipilia nigrescens*, *Titanophora pikeana*, *Callyspongia aerizusa*, *Chondropsis* sp. NW3, *Cliona* sp. NW1, *Craniella* sp. NW1, *Echinochalina* sp. NW1, *Iotrochota* cf. *coccinea*, *Xestospongia bergquistia*, *Xestospongia testudinaria*, *Astreopora listeri*, *Echinophyllia echiinata*, *Heliofungia actiniformis*, *Platygyra lamellina*, *Symphyllia recta*, *Pilodius pilumnoides*, *Pilumnid* sp. 3, *Isognomon isognomonum*, *Pyrene deshayesii*, *Nardoa tuberculata*, *Amblygobius decussatus*, *Aprion virescens*, *Archamia fucata*, *Atrosalarias fuscus*, *Caranx melanopygus*, *Centropyge tibicen*, *Cryptocentrus caeruleomaculatus*, *Cryptocentrus fasciatus*, *Ctenogobius feroculus*, *Ecsenius schroederi*, *Epinephelus maculatus*, *Eviota prasites*, *Gnatholepis anjerensis*, *Halichoeres prosopion*, *Pterocaesia pisang*, and *Scolopsis affinis*).

The separation of Mermaid Reef from the three northern atolls was apparent for both lagoon and reef front habitats. Eight species discriminated the reef front at the three northern atolls (South Scott, North Scott and Seringapatam Reefs) from Mermaid Reef (*Plakortia nigra*, *Favites stylifera*, *Pocillopora damicornis*, *Tetralia* sp. 1, *Cheilinus trilobatus*, *Chrysiptera rex*, *Nemateleotris magnifica*, and *Pomacentrus lepidogenys*; Table A2). Seven species discriminated the lagoon at the northern three atolls from the lagoon at Mermaid Reef (*Lithophyllon undulatum*, *Sandalolitha robusta*, *Begonia semiorbiculata*, *Aethaloperca rogaa*, *Chrysiptera rex*, *Halichoeres melanurus*, and *Lethrinus erythropterus*; Table A3).

Environmental relationships

The abiotic variables formed two groups, separating most of the lagoon stations into one group, and all of the

Table 4

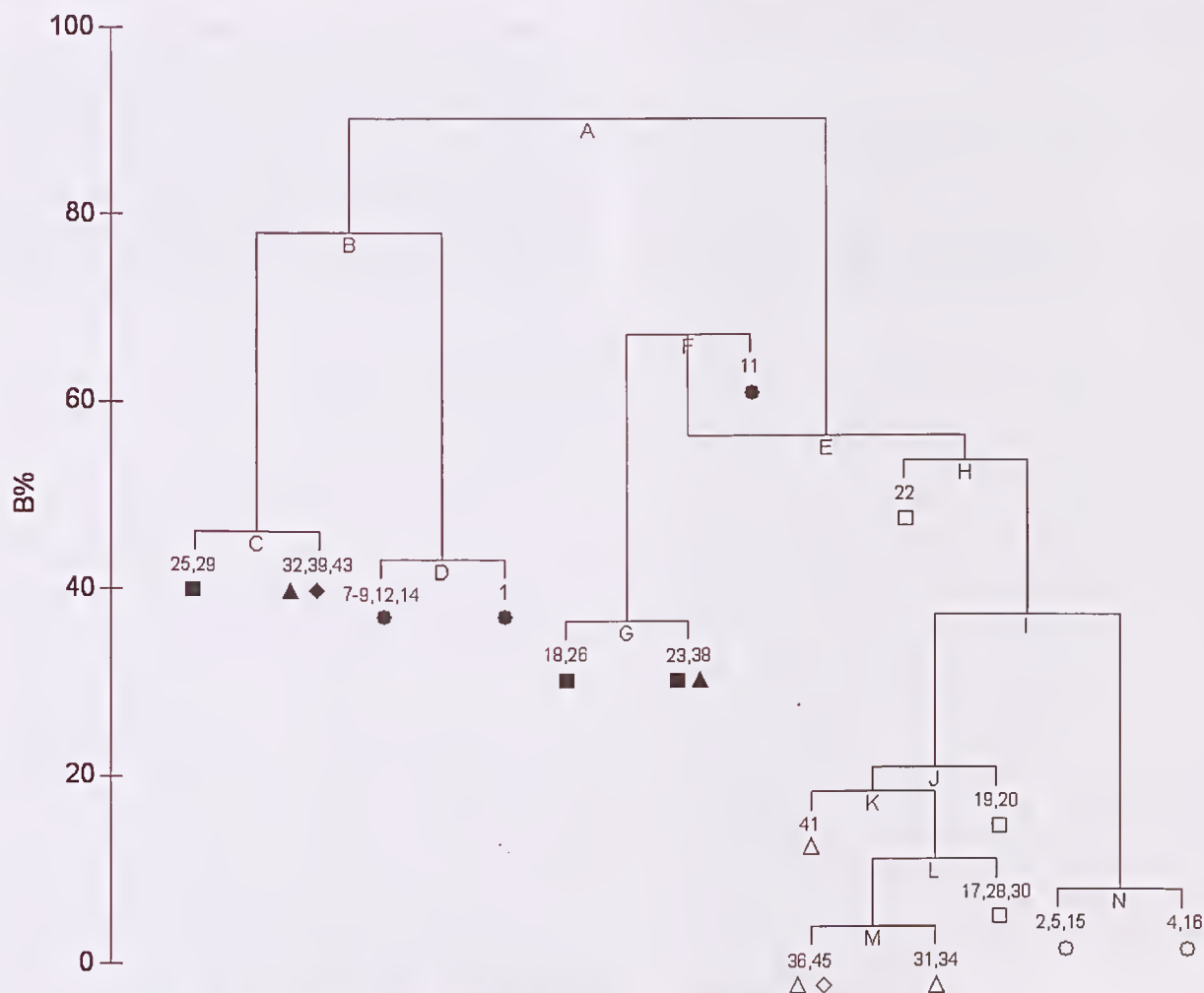
Average Bray-Curtis similarity within each atoll (a) and the average dissimilarity between atolls (b) in the lagoon and on the reef front, based on the SIMPER analysis. High % indicated greater similarity or dissimilarity. * only one station was sampled so not able to calculate a similarity.

Atoll	Average similarity/ dissimilarity	Atoll	Average similarity/ dissimilarity
Reef Front		Lagoon	
a) Average similarity		a) Average similarity	
Mermaid	57	Mermaid	48
South Scott	52	South Scott	49
North Scott	59	North Scott	53
Seringapatam	50	Seringapatam	*
b) Average dissimilarity		b) Average dissimilarity	
Mermaid, South Scott	54	Mermaid, South Scott	62
Mermaid, North Scott	54	Mermaid, North Scott	59
Mermaid, Seringapatam	54	Mermaid, Seringapatam	66
South Scott, North Scott	49	South Scott, North Scott	54
South Scott, Seringapatam	49	South Scott, Seringapatam	62
North Scott, Seringapatam	45	North Scott, Seringapatam	54

reef front stations with the addition of four lagoon stations into the other group (18, 23, 26, and 43, Fig. 4). These abiotic variables significantly explain the biological community structure (BEST, $Rho = 0.58$, $p < 0.001$).

The first split in the tree at group A separated stations that had a high proportion of rock substrate compared to those that had low percent rock (Fig. 6). Within the low

rock group, the next separation of stations (group B) occurred due to atoll separation distance, with stations from the northern atolls of Scott (North and South) and Seringapatam separating from the southern most atoll (Mermaid Reef), followed by South Scott Reef separating from the two northern atolls (North Scott and Seringapatam) (Group C, Fig. 6). The high percent rock stations separated depending on whether they were



Group	R	B%	Abiotic factor and inequality values
A	0.72	90	Rock $<0.24\%$ ($>0.27\%$)
B	0.93	78	Atoll Separation Distance <55 (>500)
C	0.67	46	Atoll Separation Distance >55 (<35)
D	0.8	43	Sand $<0.19\%$ ($>0.23\%$) or Max. Depth >11 (<10.5)
E	0.57	56	Habitat <1 (>2)
F	0.92	67	Reef Separation Dist <55 (>500) or Sand $<0.097\%$ ($>0.23\%$) or Direction Quadrant >2 (<1)
G	0.5	37	Rubble $<0.25\%$ ($>0.27\%$)
H	0.67	54	Direction Quadrant >8 (<7)
I	0.77	37	Atoll Separation Distance <55 (>500)
J	0.51	21	Direction Quadrant <5 (>7)
K	0.61	18	Rubble $>0.35\%$ ($<0.17\%$)
L	0.37	11	Atoll Separation Distance <35 (>55)
M	0.25	4	Sand $<0.027\%$ ($>0.077\%$) or Direction Quadrant <2 (>3) or Rubble $<0.007\%$ ($>0.04\%$)
N	0.58	8	Direction Quadrant <2 (>4) or Rubble $<0\%$ ($>0.14\%$)

Figure 6. LINKTREE analysis showing the divisive clustering of the stations based on the biotic community and constrained by the inequalities of one or more abiotic factors. Symbols as in Figure 3. For each split in the tree the ANOSIM R value (relative subgroup separation) and B% (absolute subgroup separation, scaled to maximum of first division) is given. The abiotic factor contributing to the split is listed with the first inequality defining the group to the left of the split and the value in brackets defining the group to the right. Habitat: 1 – lagoon, 2 – reef front; atoll separation distance (km): Seringapatam – 0, North Scott – 35, South Scott – 55, Mermaid – 500; direction quadrant: 1 – NNE, 2 – NE, 3 – SE, 4 – SSE, 5 – SSW, 6 – SW, 7 – NW, 8 – NNW.

associated with either the lagoon habitat or the reef front (group E, Fig. 6). There was a reversal, indicating that an explanatory environmental variable is missing, in the tree at group F that appeared to have been caused by the community at station 11 in Mermaid Reef lagoon. Group G consisted of lagoon stations from Scott Reef splitting into two groups based on the amount of rubble at the stations. The reef front stations showed partitioning due to exposure (direction quadrant, Group H, J and N), atoll separation (group I and L) and percent rubble or percent sand (group K, M, and N).

Correlations between each assemblage

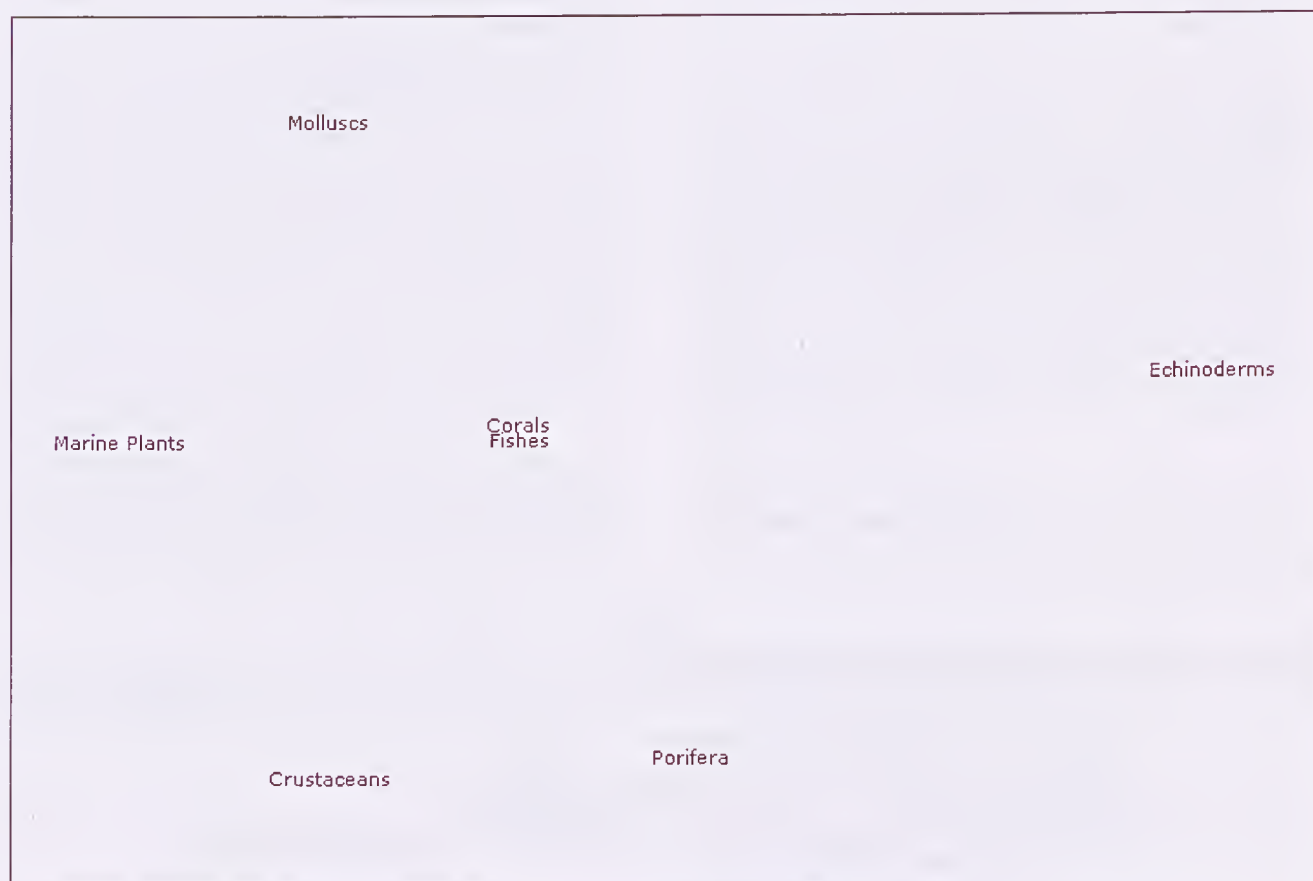
The coral and fish assemblages were highly correlated (0.79) and essentially provided the same information about the interrelationships among habitats and atolls (Fig. 7). By comparison, the other taxonomic groups were less correlated and give different information about the atolls (Fig. 7). The crustaceans had similar correlations to

marine plants, corals and sponges (~ 0.5), while echinoderms had low correlations with all the taxonomic groups examined (range 0.18 to marine plants to 0.41 with corals). Marine plants had similar correlations to fishes and molluscs (0.52).

Discussion

Community differences among habitats

The intertidal reef flat communities at each atoll were unique, with different species assemblages and low similarity to each other. However, seven species were typical of this overall habitat, comprising four species of molluscs, one of algae and two of corals. The alga, *Boodlea vanbosseae*, and the mollusc, *Cypraea moneta*, were key discriminating species for reef flat habitats, separating this habitat from the three subtidal habitats examined. Both these species are widespread in the Indo-West



TaxaGroup	Porifera	Fishes	Crustaceans	Molluscs	Echinoderms	Corals
Fishes	0.66					
Crustaceans	0.44	0.55				
Molluscs	0.36	0.59	0.35			
Echinoderms	0.28	0.30	0.26	0.23		
Corals	0.53	0.79	0.59	0.59	0.41	
Marine Plants	0.39	0.52	0.47	0.52	0.18	0.59

Figure 7. Second stage nMDS plot for each floral and faunal assemblage and the Spearman correlations underlying the nMDS plot. Stress 0.03.

Pacific and known inhabitants of the intertidal zone. Intertidal species may be more vulnerable to climate change than subtidal species as they are already likely to be living at their physiological limits (Harley *et al.* 2006). In these isolated atolls possibly subject to increasing cyclone events, significant changes in intertidal species assemblages should be anticipated and monitoring of these key species could aid in early detection of change in these assemblages.

The subtidal habitats also showed differences in community composition with all stations within a habitat grouping together. The reef front community assemblages were most similar and the tidal channel community assemblages the least similar. A number of plant, coral, mollusc and fish species typified the reef front but none were characteristic of this habitat alone. However, we did detect differences in average presence between the reef front and lagoon community assemblages, with eight species (one coral, one mollusc and six fish) being consistently more typical of the reef front than the lagoons. In addition, three species consistently discriminated the lagoon habitat from all other habitats. The lagoon and reef front habitats had clear structural differences in their community assemblages, with more variation between lagoon stations than reef front stations. This variability in lagoon habitats has been documented for six atolls in the Tuamotu Archipelago (French Polynesia) where coral, fish, mollusc and echinoderm assemblages were surveyed in six predefined lagoon habitats and four assemblages were identified (Pante *et al.* 2006). However, we found very few references on tropical marine community assemblages and suggest more studies of this type are essential.

Marine communities have traditionally been viewed as 'open' with a large degree of connectivity between populations but increasingly studies are suggesting that there may be high levels of self recruitment in some populations (Sponaugle *et al.* 2002). A range of factors have been identified as correlates of self-recruitment, for example adult fecundity, spawning and larval release patterns (spatial and temporal), parental investment and development of larval stage at hatching, pelagic larval duration, larval behaviour and sensory capabilities, geographic site isolation, flow variability and water column stratification (Sponaugle *et al.* 2002). In particular some studies have shown that atoll lagoons may have higher levels of self-recruitment than some other habitats such as the reef front. This idea has found support in studies on west Pacific atolls examining the distribution and size structure (Leis 1994; Leis *et al.* 1998) and genetics (Planes *et al.* 1998) of larval fishes, and corals on the Great Barrier Reef (see Ayre and Duffy 1994 in Underwood *et al.* 2007). We found the lagoon community assemblages on the northern Western Australian atolls had a higher number of unique species than the reef front habitats, in particular in Mermaid Reef lagoon. Therefore, enclosed lagoon habitats at these atolls may pose more of a barrier to dispersal than the reef front environments, and preclude dispersal of species with short-lived or non pelagic larvae. Genetic studies on a wide range of taxa with a variety of reproductive strategies that reside in these lagoons could test this hypothesis.

In this study, we have highlighted some species

associated with particular habitats that could serve as sentinels of change. Although the key discriminating species were largely fishes and corals in the subtidal habitats examined in this study, this was not the case for the intertidal habitat. Consequently, the baseline monitoring of fishes and corals at the three northern atolls of South Scott, North Scott and Seringapatam Reefs (Heyward *et al.* 2007) would seem appropriate for the subtidal habitats, but the inclusion of some mollusc, crustacean, and plant species would enhance monitoring programs in the intertidal. Furthermore, for the majority of the species present at these atolls almost nothing is known about their biology, reproduction, behaviour, and larval life histories and it would be very useful to conduct such studies for the key species we identified as indicative of certain habitats.

Community turnover between atolls

In addition to significant differences in species assemblages in some of the habitats studied, species assemblages were significantly different among atolls. We found clear differences in the species present at Mermaid Reef, which separated it from the northern atolls of South Scott, North Scott and Seringapatam Reefs. This suggests that the large distance from Mermaid Reef to the more northern atolls (~500 km) may preclude dispersal by some species. A latitudinal gradient of species diversity and composition declining southward has been discussed for northern Western Australia (Wilson & Allen 1987; Wells & Allen 2005). South Scott Reef was the largest atoll studied, with three of the four habitats examined, and the second highest number of stations after Mermaid Reef. The difference in species richness between South Scott and Mermaid Reefs, which had similar sampling effort, could be due to a latitudinal gradient in species diversity. This was suggested for fishes by Moore & Morrison (2009), who found higher fish diversity in the northern atolls, as did Bryce and Whisson (2009) for molluscs. Moreover, Mermaid Reef had more unique species, such as the alga *Cladophora herpestica* (Huisman *et al.* 2009), which was not found in the northern atolls and 24 species of crustaceans (Titelius *et al.* 2009) and sponges (Fromont & Vanderklift 2009) were unique to this atoll.

All the atolls, except South Scott Reef appeared to have distinct species assemblages. Distinct sponge communities have been previously reported for other nearby atolls such as Ashmore, Cartier and Hibernia Reefs (Hooper 1994), and our results suggest that for many taxa groups, distinct species assemblages are characteristic of these offshore atolls. Distinct assemblages at different atolls have also been documented in French Polynesia and indicates that marine reserve design based solely on representativeness would require the protection of the majority of atolls and habitats (Pante *et al.* 2006).

The scientists involved in this study in some instances reported on numerous rare species; for example, 169 species of corals were reported from fewer than 10 of the 45 stations sampled, with only 22 species being abundant (found at more than 25 stations), (McKinney 2009), 79 species of sponges were found only at one of the atolls, and only 14 species could be considered widespread and common (Fromont & Vanderklift 2009), and the majority

of the crustacean species were rare with most recorded from fewer than three stations (Titelius *et al.* 2009). Although 124 mollusc species were common to all four atolls studied, many species were found only at one of the atolls (Bryce & Whisson 2009). These findings of a large number of rare species gives support to what is already known for terrestrial environments (Rabinowitz *et al.* 1986; Howe 1999) and which is being increasingly reported in marine environments (Gray *et al.* 2005; Fromont *et al.* 2006 and references therein). Echinoderms were rare and frequently sparse in the environments surveyed. However, they were collected in conjunction with molluscs and consequently received a much lower sampling effort than the other taxonomic groups, which may in part account for this rarity and low abundance.

Environmental drivers and assemblage correlations.

Cross-shelf differences in both species richness and community composition have been commented on for the Kimberley region (Marsh & Marshall 1983; Hutchins 1999; Hutchins 2001; Huisman *et al.* 2009; Moore & Morrison 2009). Faunal species richness on the atolls was higher than on the coastal Kimberley reefs and different species occurred on the atolls compared to the Kimberley coast, both for echinoderms (Marsh & Marshall 1983) and fishes (Hutchins 1999; Hutchins 2001). In contrast, this pattern was reversed for algae, with higher species richness along the coast compared to the atolls (Huisman *et al.* 2009). However, these comparisons were based on total species richness and were not partitioned by habitat or adjusted species richness calculations for unequal sampling effort. New species richness assessments of this data (with unequal sampling effort addressed) suggest that some taxa groups are more diverse in subtidal habitats on the offshore atolls than on the Kimberley coast but diversity is more variable in the intertidal and may not follow the same trend (Sampey *et al.* unpublished data). Compared to the oligotrophic environment of the offshore atolls, the Kimberley coast can have high nutrient, sediment and freshwater flows, and as a result the waters are turbid with high levels of flocculating silt on the reefs. The differences in species richness and community assemblages found among the same habitats on the atolls compared to the coast suggest that different abiotic factors contribute to the maintenance of assemblages. These are likely to be environmental aspects (such as degree of turbidity, siltation, tolerance to freshwater, and desiccation exposure) and differences in the tolerances, recruitment and survivorship of the different taxonomic groups to such environmental conditions.

In the north-west atolls study, the authors detected differences in species assemblages (sponges, Fromont & Vanderklift 2009, corals, McKinney 2009, molluscs, Bryce & Whisson 2009, crustaceans, Titelius *et al.* 2009 and fishes, Moore & Morrison 2009) and suggested these differences could be attributed to a number of factors: habitat requirements (reef flat vs. lagoon vs. tidal channel vs. reef front as well as microhabitats) (Bryce & Whisson 2009; Fromont & Vanderklift 2009; McKinney 2009; Moore & Morrison 2009; Titelius *et al.* 2009), latitudinal gradients in species richness (Bryce & Whisson 2009; Fromont & Vanderklift 2009; McKinney 2009; Moore & Morrison 2009; Titelius *et al.* 2009), and influences of

cyclonic activity (i.e. exposure) (Bryce & Whisson 2009; Moore & Morrison 2009; Titelius *et al.* 2009). However, none of these factors were previously explicitly explored except for corals. In this study, our analyses have explored the link between the biotic community and abiotic environmental factors. We detected that substrate type was the principal abiotic variable influencing the biotic community assemblages, and atoll separation distance was also important for assemblages where percent of hard substrate was low, as was habitat type (lagoon vs. reef front) for assemblages where percent of hard substrate was high. These results are not surprising as many species will have a substrate preference such as corals and sponges that require a hard substrate as an attachment point, and other species which live amongst rubble or sand. Within the lagoon habitat there was high substrate variability, as the area sampled might have been on a lagoon bommie, slope or sand flat with varying amounts of fracturing of the reef and incursions of sand (Bryce, 2009). These factors will influence the species assemblages that can occur there.

Coral and fish species are the most studied taxa in tropical ecosystems (Przeslawski *et al.* 2008), yet our data found that the interrelationships of habitat and atolls for these two assemblages were highly correlated. By contrast, the other taxonomic groups had varying correlations with corals, fishes and each other, and thus provide additional information about these habitats and atolls. For example, crustaceans had similar correlations to marine plants, corals and sponges, which may be due to some crustacean species being associated with one of the sessile taxonomic groups, such as species of *Tetralia* that are associated with acroporid corals and species of pilumnid crabs that are associated with sponges (Titelius *et al.* 2009). This has important implications for management and monitoring of change at these atolls and implies that using corals and fishes as surrogates for other taxonomic groups is insufficient.

Conclusions

In this study, we focussed on exploring differences in community composition among habitats and atolls using presence absence data in a non-parametric framework with a view to providing useful insights into the communities that occur there. It would be useful in future surveys to sample with a standardised methodology and a balanced sample design to enable more rigorous comparisons.

Overall, this synthesis study has presented a sound baseline dataset of species assemblages occurring at these atolls. We have clearly demonstrated that habitats have characteristic community assemblages and that atolls have different species assemblages in some of these habitats, particularly in the lagoon and reef flat environments. In some habitats the common taxa groups (fishes and corals) may provide adequate information for the overall species assemblages and can be used as surrogates, but in other cases, e.g. in the intertidal, these commonly targeted groups are far less useful in reflecting overall community patterns.

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Appendix

The typifying and discriminating species identified with the SIMPER analyses are presented here. Species from all taxonomic groups were restricted to certain habitats (Table A1). Within the lagoon (Table A2) and reef front (Table A3) habitats some species were restricted to certain atolls and there were more unique species at an atoll in the lagoon habitat than the reef front habitats.

Table A1

Typifying (T) and discriminating (D) species for each habitat.

The habitat that a species typifies (Average presence of ~1, i.e. present in most stations from that habitat) is listed first and then the habitats that it discriminates from are listed in brackets (Dissimilarity/SD ratio of ~1; i.e. absent from that habitat). Habitats: Fl – reef flat, TC – tidal channel, Fr – reef front, L – lagoon.

Species	T (D)	Species	T (D)
Marine Plants		Fishes	
<i>Boodlea vanbosseae</i>	Fl (TC, Fr, L)	<i>Acanthurus nigricans</i>	TC, Fr (Fl, L)
<i>Halimeda muvima</i>	Fr, L (Fl, TC)	<i>Acanthurus olivaceus</i>	TC (Fl, L)
<i>Hydrolithon onkodes</i>	Fr (Fl, L)	<i>Aethaloperca rogaa</i>	TC (Fl)
<i>Turbiularia ornata</i>	Fl (TC, Fr)	<i>Balistapus undulatus</i>	TC, Fr (Fl)
<i>Valonia ventricosa</i>	Fr (Fl, TC)	<i>Bodianus axillaris</i>	TC (Fl, L)
Sponges		<i>Bodianus diana</i>	TC (Fl, Fr, L)
<i>Cliona orientalis</i>	TC (Fl, L)	<i>Cephalopholis argus</i>	TC, Fr (Fl)
<i>Lamellosysidea herbacea</i>	TC, Fr (Fl)	<i>Cephalopholis nrodeta</i>	Fr (L)
<i>Jaspis splendens</i>	TC (Fl)	<i>Chaetodon auriga</i>	TC, L (Fl)
Corals		<i>Chaetodon citrinellus</i>	TC (Fl, L)
<i>Acropora abrolhosensis</i>	L (Fl, TC, Fr)	<i>Chaetodon ephippium</i>	TC (Fl)
<i>Acropora digitifera</i>	Fl (TC, L)	<i>Chaetodon lunula</i>	TC (Fl)
<i>Acropora humilis</i>	Fr	<i>Chaetodon lunulatus</i>	TC, Fr (Fl)
<i>Acropora intermedia</i>	L (Fl, TC)	<i>Chaetodon ornatissimus</i>	TC, Fr (Fl)
<i>Acropora nasuta</i>	Fr	<i>Chaetodon punctatofasciatus</i>	Fr (L)
<i>Acropora spicifera</i>	Fr (Fl)	<i>Chaetodon nlietensis</i>	TC (Fl)
<i>Echinopora lamellosa</i>	Fr (Fl, TC)	<i>Cheilinus undulatus</i>	TC (Fl, L)
<i>Favia matthaii</i>	Fr (Fl)	<i>Chromis margaritifer</i>	TC (Fl)
<i>Favia pallida</i>	Fr (TC)	<i>Chromis weberi</i>	TC (Fl)
<i>Favia stelligera</i>	Fr (Fl)	<i>Chromis xanthura</i>	Fr (L)
<i>Favites abdita</i>	Fr (Fl)	<i>Ctenochaetus striatus</i>	Fr, L (Fl)
<i>Galaxea fascicularis</i>	Fr, L (Fl)	<i>Dascyllus aruanus</i>	L (Fl, TC, Fr)
<i>Goniastrea pectinata</i>	Fr (Fl)	<i>Forcipiger flavissimus</i>	TC, Fr (Fl, L)
<i>Goniastrea retiformis</i>	Fr	<i>Forcipiger longirostris</i>	TC (Fl, L)
<i>Isopora palifera</i>	Fr (Fl, L)	<i>Gomphosus varius</i>	TC (Fl)
<i>Lobophyllia hemprichii</i>	L (Fl)	<i>Halichoeres hortulanus</i>	TC, Fr (Fl)
<i>Montastrea curta</i>	Fr (Fl)	<i>Labroides dimidiatus</i>	TC, Fr, L (Fl)
<i>Montastrea magnistellata</i>	L (Fl)	<i>Lethrinus olivaceus</i>	TC (Fl)
<i>Pavona varians</i>	Fr (Fl)	<i>Lutjanus bohar</i>	TC (Fl)
<i>Pocillopora eydouxi</i>	TC (Fl, L)	<i>Lutjanus decussatus</i>	Fr (Fl)
<i>Pocillopora verrucosa</i>	Fr (Fl)	<i>Lutjanus gibbus</i>	Fr
<i>Porites vaughani</i>	Fr (L)	<i>Macropharyngodon meleagris</i>	TC (Fl)
<i>Psammocora profundacella</i>	Fr	<i>Monotaxis grandoculis</i>	TC, Fr, L (Fl)
Crustaceans		<i>Naso caesi</i>	Fr (L)
<i>Calcinus gainardii</i>	TC (Fr, L)	<i>Naso lituratus</i>	TC, Fr, L (Fl)
<i>Calcinus minutus</i>	Fr	<i>Nemateleotris magnifica</i>	TC (L)
Molluscs		<i>Parupeneus barberi</i>	TC (Fl)
<i>Arca avellana/ventricosa</i>	L (TC)	<i>Parupeneus crassilabris</i>	Fr (TC, L)
<i>Cerithium echinatum</i>	Fr (L)	<i>Parupeneus multifasciatus</i>	Fr (Fl)
<i>Conus miles</i>	Fr	<i>Pomacanthus imperator</i>	TC (Fl, Fr, L)
<i>Conus miliaris</i>	Fl (L)	<i>Pomacentrus moluccensis</i>	L (Fl, TC, Fr)
<i>Coralliophila neritoidea</i>	Fr	<i>Pomacentrus philippinus</i>	TC, Fr (Fl)
<i>Cypraea moneta</i>	Fl (TC, Fr, L)	<i>Pomacentrus vaiuli</i>	TC (Fl)
<i>Drupella coruus</i>	Fr (Fl)	<i>Pseudocheilinus hexataenia</i>	Fr (Fl, TC)
<i>Lambis chiragra</i>	Fl (Fr, L)	<i>Pygoplites diacanthus</i>	Fr (Fl)
<i>Tridacna crocea</i>	Fl, Fr, L	<i>Sargocentron spiniferum</i>	TC (Fl)
<i>Tridacna maxima</i>	Fr, L	<i>Scolopsis bilineata</i>	TC (Fl)
<i>Turbo argyrostomus/chrysostomus</i>	Fr (L)	<i>Stethojulis bandanensis</i>	TC (Fr, L)
<i>Vasum turbinellum</i>	Fr	<i>Stiffamen bursa</i>	TC (Fl, L)
Echinoderms		<i>Thalassoma amblycephalum</i>	TC, Fr (Fl)
<i>Echinometra mathiae</i>	TC	<i>Thalassoma hardwicke</i>	L (Fl)
		<i>Thalassoma quinquevittatum</i>	Fr (L)
		<i>Zanclus cornutus</i>	TC, Fr (Fl)

Table A2

Typifying (T) and discriminating (D) species for each atoll in the reef front habitat.

The atoll that a species typifies is listed first and then the atolls that it discriminates from are listed in brackets. Atolls: ME – Mermaid Reef, SS – South Scott Reef, NS – North Scott Reef, and SE – Seringapatam Reef.

Species	T (D)	Species	T (D)
Marine Plants		Molluscs cont.	
<i>Cladophora herpestica</i>	ME (SE)	<i>Drupa ricinus</i>	ME, SS (SE)
<i>Dichotomaria marginata</i>	NS (ME)	<i>Drupina grossularia</i>	SE (ME)
<i>Haloplegma duperreyi</i>	SE (ME, SS, NS)	<i>Latirus turritus</i>	ME, SS (SE)
<i>Neomeris bilinubata</i>	SS, NS (ME)	<i>Lioconcha castreusis</i>	NS (ME, SS, SE)
<i>Pterocladia caerulea</i>	SE (ME, SS, NS)	<i>Morula biconica</i>	NS, SE (ME)
<i>Tricleocarpa cylindrica</i>	NS, SE (ME)	<i>Morula uva</i>	ME (SS, NS, SE)
Sponges		<i>Phyllidia coelestis</i>	SS (ME, SE)
<i>Cliona orientalis</i>	SE (ME)	<i>Pinna bicolor</i>	NS (ME, SS, SE)
<i>Gelliodes fibulata</i>	NS, SE (ME)	<i>Rhinoclavis aspera</i>	NS (ME, SS)
<i>Halichondria</i> sp. NW2	NS (ME, SE)	<i>Septifer bilocularis</i>	NS (ME)
<i>Hyrtios erecta</i>	NS (ME, SE)	<i>Streptopium saccata</i>	NS, SE (ME)
<i>Monanchora unguiculata</i>	SS, SE (ME)	<i>Tectus pyramis</i>	SS, NS, SE (ME)
<i>Myrmekioderma granulata</i>	SE (ME, SS)	Fishes	
<i>Niphates</i> sp. NW1	NS, SE (ME)	<i>Acanthurus blochii</i>	SE (ME)
<i>Niphates</i> sp. NW4	NS (ME, SS, SE)	<i>Acanthurus uigricauda</i>	SE (ME)
<i>Plakortis nigra</i>	SS, NS, SE (ME)	<i>Acanthurus nigrofusus</i>	SE (ME)
<i>Neopetrosia exigua</i>	NS (ME, SS)	<i>Acanthurus pyroferus</i>	NS (ME)
Corals		<i>Canthigaster solandri</i>	SE (ME, SS)
<i>Acanthastrea brevis</i>	NS (ME, SS, SE)	<i>Caranx melampygus</i>	ME, SE (SS)
<i>Acropora polystoma</i>	ME (SS, NS)	<i>Centropyge bicolor</i>	SE (ME)
<i>Acropora samoensis</i>	NS (ME, SE)	<i>Centropyge vrolikii</i>	SS, SE (ME)
<i>Acropora subulata</i>	NS, SE (ME)	<i>Chaetodon adiergastos</i>	ME (SS, NS, SE)
<i>Astreopora myriophthalma</i>	NS (ME)	<i>Chaetodon oxycephalus</i>	SE (ME)
<i>Ctenactis echinata</i>	NS (ME, SS, SE)	<i>Chaetodon trifascialis</i>	ME (NS)
<i>Favites stylifera</i>	SS, NS, SE (ME)	<i>Chaetodon unimaculatus</i>	ME (SS, NS, SE)
<i>Fungia fungites</i>	NS (ME, SS)	<i>Chaetodon vagabundus</i>	NS, SE (ME)
<i>Heliopora coerulea</i>	SS, SE (ME)	<i>Cheilinus fasciatus</i>	ME, SE (SS)
<i>Isopora brueggemauni</i>	ME, NS (SS)	<i>Cheilinus trilobatus</i>	SS, NS, SE (ME)
<i>Leptastrea aequalis</i>	NS, SE (ME, SS)	<i>Cheilodipterus quinquelineatus</i>	NS (ME, SS, SE)
<i>Leptoseris scabra</i>	NS (ME, SE)	<i>Chrysiptera rex</i>	SS, NS, SE (ME)
<i>Lithophyllon undulatum</i>	SS, NS (ME)	<i>Cirrhitilabrus exquisitus</i>	SS, SE (ME)
<i>Merulina scabricula</i>	ME (SE)	<i>Coris gaimard</i>	NS, SE (ME)
<i>Platygyra daedalea</i>	SS (ME, NS)	<i>Forcipiger longirostris</i>	NS (SE)
<i>Pocillopora damicornis</i>	SS, NS, SE (ME)	<i>Halichoeres melanurus</i>	ME, NS (SS, SE)
<i>Pocillopora eydouxi</i>	SS, SE (ME)	<i>Halichoeres nebulosus</i>	SE (ME, SS, NS)
<i>Pocillopora meandrina</i>	SE (SS)	<i>Halichoeres prosopion</i>	NS (ME)
<i>Psammocora digitata</i>	SE (SS)	<i>Hemigymnus fasciatus</i>	ME (SS)
<i>Psammocora haimcana</i>	ME (SS, NS)	<i>Hemigymnus melapterus</i>	ME (NS, SE)
<i>Psammocora superficialis</i>	SE (ME, SS)	<i>Labroides pectoralis</i>	ME (SS, NS)
<i>Turbinaria reniformis</i>	SS (ME), NS (ME)	<i>Letrinus erythropterus</i>	NS (ME)
<i>Turbinaria stellulata</i>	SE (ME)	<i>Lutjanus rivulatus</i>	ME (SS, NS, SE)
Crustaceans		<i>Macolor macularis</i>	NS, SE (SS)
<i>Calcinus lineapropodus</i>	NS (ME)	<i>Meiacanthus atrodorsalis</i>	NS (ME, SS)
<i>Chlorodiella ? laevis</i>	SS, SE (ME)	<i>Melichthys vidua</i>	ME (NS, SE)
<i>Haplocarcinus marsupialis</i>	SE (ME, SS)	<i>Nemateleotris magnifica</i>	SS, NS, SE (ME)
<i>Pilodius</i> sp. 1	SS, SE (ME)	<i>Odonus niger</i>	NS (ME)
<i>Tetralia fulva</i>	SE (ME)	<i>Parapercis millepunctata</i>	SE (ME)
<i>Tetralia</i> sp. 1	SS, NS, SE (ME)	<i>Parupeneus barberinus</i>	NS (ME)
<i>Trapezia guttata</i>	NS, SE (ME, SS)	<i>Plectroglyphidodon dickii</i>	ME (NS)
<i>Trapezia septata</i>	NS (SE)	<i>Plectroglyphidodon lacrymatus</i>	SE (ME, NS)
<i>Trapezia tigrina</i>	ME (SS, SE)	<i>Plectropomus oligacanthus</i>	NS (ME)
Molluscs		<i>Pomacentrus amboinensis</i>	NS (ME, SS, SE)
<i>Barbatia</i> aff. <i>coma</i>	NS (ME, SS, SE)	<i>Pomacentrus lepidogenys</i>	SS, NS, SE (ME)
<i>Barbatia foliata</i>	NS (ME, SE)	<i>Pseudocheilinus octotaenia</i>	NS (ME)
<i>Begonia semiorbiculata</i>	NS (ME)	<i>Siganus puellus</i>	SE (SS)
<i>Chicoreus brunneus</i>	NS (ME, SS, SE)	<i>Stethojulis bandanensis</i>	SE (ME, SS, NS)
<i>Chromodoris elisabethina</i>	ME (NS, SE)	<i>Stethojulis strigiventer</i>	ME (SS, SE)

Table A3

Typifying (T) and discriminating (D) species for each atoll in the lagoon habitat.

Notation as in Table A2. NB. Seringapatam Reef – only one station was sampled in this habitat so typifying species could not be calculated, these are inferred from the species that distinguished this atoll from the others.

Species	T (D)	Species	T (D)
Marine Plants		Corals continued	
<i>Actinotriclia fragilis</i>	SE (SS, NS)	<i>Favia helianthoides</i>	NS (SS, SE)
<i>Amphiroa fragilissima</i>	SE (ME, SS, NS)	<i>Fungia fungites</i>	NS (SE)
<i>Avrainvillea amadelpha</i>	NS (ME, SS, SE)	<i>Fungia horrida</i>	ME, NS (SE)
<i>Dictyota friabilis</i>	NS, SE (ME)	<i>Goniastrea retiformis</i>	ME, SS (SE)
<i>Ganonema farinosum</i>	SS (ME, NS, SE)	<i>Heliopora actiniiformis</i>	SE (ME, SS, NS)
<i>Hydrolithon gardineri</i>	SE (ME, SS)	<i>Isopora brueggemauni</i>	ME (SE)
<i>Lobophora variegata</i>	SS, NS (SE)	<i>Lithophyllon mokai</i>	SE (ME, SS)
<i>Rhipilia crassa</i>	SE (ME, SS, NS)	<i>Lithophyllon undulatum</i>	SS, NS, SE (ME)
<i>Rhipilia nigrescens</i>	SE (ME, SS, NS)	<i>Merulina scabridula</i>	NS (SE)
<i>Symploca hydroides</i>	SE (ME, SS)	<i>Montastrea curta</i>	SS (ME, NS, SE)
<i>Titanopora pikeana</i>	SE (ME, SS, NS)	<i>Montipora iucassata</i>	SE (ME, NS)
<i>Udotea glaucescens</i>	ME (SS, NS)	<i>Montipora iuformis</i>	SE (ME)
<i>Valonia ventricosa</i>	SS, NS (ME)	<i>Montipora tuberculosa</i>	SS (SE)
Sponges		<i>Montipora turgescens</i>	SE (ME, NS)
<i>Callyspongia aerizusa</i>	SE (ME, SS, NS)	<i>Mycedium elephantotus</i>	SS (ME, SE)
<i>Chondropsis</i> sp. NW3	SE (ME, SS, NS)	<i>Oulophyllia bennettiae</i>	SE (SS, NS)
<i>Cliona</i> sp. NW1	SE (ME, SS, NS)	<i>Pachyseris rugosa</i>	SE (ME)
<i>Craniella</i> sp. NW1	SE (ME, SS, NS)	<i>Pachyseris speciosa</i>	SS (SE), NS (ME, SE)
<i>Echinoclathra</i> sp. NW1	SE (ME, SS, NS)	<i>Pavona varians</i>	ME, SS (SE)
<i>Haliclona</i> sp. NW5	SE (ME, NS)	<i>Physogyra lichtensteini</i>	ME, NS, SE (SS)
<i>Hyrtios crecla</i>	SS (ME)	<i>Platygyra lamellina</i>	SE (ME, SS, NS)
<i>Iotrochota</i> cf. <i>coccinea</i>	SE (ME, SS, NS)	<i>Pocillopora verrucosa</i>	SS (ME, NS, SE)
<i>Xestospongia bergquistia</i>	SE (ME, SS, NS)	<i>Podabacia crustacea</i>	NS, SE (ME, SS)
<i>Neopetrosia exigua</i>	ME, NS (SE)	<i>Porites lobata</i>	SS, NS (SE)
<i>Xestospongia testudinaria</i>	SE (ME, SS, NS)	<i>Porites monticulosa</i>	SE (ME, SS)
Corals		<i>Sandalolithia robusta</i>	SS, NS, SE (ME)
<i>Acropora abrolhosensis</i>	ME, SS, NS (SE)	<i>Seriatopora lystris</i>	ME, SS, NS (SE)
<i>Acropora caroliniana</i>	SS (ME), SE (SS, NS)	<i>Stylophora pistillata</i>	ME, SS (NS, SE)
<i>Acropora cerealis</i>	NS (SE)	<i>Symphyllia recta</i>	SE (ME, SS, NS)
<i>Acropora granulosa</i>	SS (ME), SE (NS)	<i>Turbinaria frondens</i>	SE (ME, SS)
<i>Acropora humilis</i>	ME, SS (SE)	Crustaceans	
<i>Acropora hyacinthus</i>	SS (NS, SE)	<i>Calcinus lineapropodus</i>	NS (SE)
<i>Acropora microphthalmia</i>	ME, SS, NS (SE)	<i>Calcinus minutus</i>	SS (ME, SE)
<i>Acropora muricata</i>	SS (SE)	<i>Chlorodiella ? cytherea</i>	ME (NS, SE)
<i>Acropora nasuta</i>	ME, SS (SE)	<i>Chlorodiella ? laevissima</i>	SE (ME, SS)
<i>Acropora spicifera</i>	SS (NS, SE)	<i>Gaillardiculus</i> sp. 1	SE (ME, SS)
<i>Acropora tenuis</i>	ME, SS (NS, SE)	<i>Haplocarcinus marsupialis</i>	NS, SE (ME)
<i>Astreopora cucullata</i>	NS (ME, SE)	<i>Pilodius pilumnoides</i>	SE (ME, SS, NS)
<i>Astreopora gracilis</i>	SS, SE (ME)	<i>Pilodius</i> sp. 1	SS (ME, NS, SE)
<i>Astreopora listeri</i>	SE (ME, SS, NS)	<i>Pilumnid</i> sp. 3	SE (ME, SS, NS)
<i>Australomussa rowleyensis</i>	SE (ME, SS)	<i>Tetralia fulva</i>	SS (ME, SE)
<i>Echinophyllia aspera</i>	SE (ME, SS)	<i>Tetralia</i> sp. 1	SS (SE), NS (ME, SE)
<i>Echinophyllia echinata</i>	SE (ME, SS, NS)	<i>Tiarina ? cornigera</i>	SS (NS, SE)
<i>Echinopora horrida</i>	SS (ME, NS, SE)	<i>Trapezia guttata</i>	NS, SE (ME)
<i>Echinopora lamellosa</i>	ME, SS, NS (SE)	<i>Trapezia septata</i>	SS (ME, NS, SE)
<i>Echinopora mammiiformis</i>	SE (ME, NS)		

Table A3 continued over

Table A3 (cont.)

Species	T (D)	Species	T (D)
Molluscs		Fishes continued	
<i>Arca avellana/ventricosa</i>	ME, SS, NS (SE)	<i>Chaetodon trifascialis</i>	ME (SE)
<i>Barbatia aff. coma</i>	NS (ME, SS, SE)	<i>Cheilodipterus artus</i>	SE (ME, SS)
<i>Beguinia semiorbiculata</i>	SS, NS, SE (ME)	<i>Cheilodipterus macrodon</i>	SE (ME, NS)
<i>Conus capitaneus</i>	SE (ME, SS)	<i>Chrouis xanthura</i>	SS (ME, NS, SE)
<i>Conus miles</i>	SS (ME, SE)	<i>Chrysiptera rex</i>	SS, NS, SE (ME)
<i>Conus musicus</i>	SS (ME, SE)	<i>Coris batueusis</i>	SE (ME)
<i>Cypraea erosa</i>	NS (ME, SS, SE)	<i>Cryptocentrus caeruleomaculatus</i>	SE (ME, SS, NS)
<i>Drupella cornus</i>	ME, SS, NS (SE)	<i>Cryptocentrus fasciatus</i>	SE (ME, SS, NS)
<i>Isogomom isogomomum</i>	SE (ME, SS, NS)	<i>Ctenogobiops feroculus</i>	SE (ME, SS, NS)
<i>Morula spinosa</i>	SE (ME)	<i>Dascyllus reticulatus</i>	SS (ME, SE)
<i>Octopus cyaneus</i>	SE (SS, NS)	<i>Dascyllus trimaculatus</i>	SS (ME, SS, SE)
<i>Phyllidiella pustulosa</i>	SE (ME, SS)	<i>Dischistodus perspicillatus</i>	ME (SS, SE)
<i>Pyreue deshayesii</i>	SE (ME, SS, NS)	<i>Ecseuius schroederi</i>	SE (ME, SS, NS)
<i>Septifer bilocularis</i>	NS, SE (ME)	<i>Epinephelus maculatus</i>	SE (ME, SS, NS)
<i>Streptopinna saccata</i>	SS (ME)	<i>Epinephelus ongus</i>	SE (ME, SS)
<i>Tridacna derasa</i>	ME (SS, NS)	<i>Epinephelus polyphkadion</i>	ME (SS, SE)
<i>Vasum turbinellum</i>	NS (ME, SS, SE)	<i>Eviota prasites</i>	SE (ME, SS, NS)
Echinoderms		<i>Gnatholepis anjerensis</i>	SE (ME, SS, NS)
<i>Bohadschia argus</i>	ME (SS, SE)	<i>Gomphosus varius</i>	ME, NS (SS, SE)
<i>Echinaster luzonicus</i>	SE (NS)	<i>Halichoeres melanurus</i>	SS, NS, SE (ME)
<i>Eucidaris metularia</i>	SE (ME)	<i>Halichoeres prosopoeion</i>	SE (ME, SS, NS)
<i>Holothuria (Halodeima) atra</i>	ME (SE)	<i>Halichoeres trimaculatus</i>	ME, SE (SS)
<i>Holothuria (Halodeima) edulis</i>	ME, SS (SE)	<i>Heniochus chrysostomus</i>	SS (ME, SE)
<i>Nardoa tuberculata</i>	SE (ME, SS, NS)	<i>Labrichthys unilineatus</i>	ME, SS (NS, SE)
<i>Ophiactis savignyi</i>	SE (ME, SS)	<i>Lethrinus erythropterus</i>	SS, NS, SE (ME)
<i>Pearsonothuria graeffei</i>	ME (SE)	<i>Lutjanus decussatus</i>	SS, NS (ME)
Fishes		<i>Lutjanus gibbus</i>	NS, SE (ME)
<i>Acanthurus nigricans</i>	SS (ME, NS, SE)	<i>Monotaxis grandoculis</i>	ME, SS, NS (SE)
<i>Acanthurus nigricauda</i>	SS (ME), SE (SS, NS)	<i>Plectroglyphidodon lacrymatus</i>	SS, NS (ME, SE)
<i>Aethaloperca rogaa</i>	SS, NS, SE (ME)	<i>Plectropomus areolatus</i>	NS, SE (SS)
<i>Amblygobius decussatus</i>	SE (ME, SS, NS)	<i>Pomacentrus adelus</i>	ME, SS (SE)
<i>Amblygobius nocturnus</i>	SE (ME, SS)	<i>Pomacentrus amboiueusis</i>	NS, SE (ME, SS)
<i>Amblygobius phalaena</i>	ME (SS, NS, SE)	<i>Pomacentrus lepidogenys</i>	SS, NS (ME, SE)
<i>Amblygobius rainfordi</i>	NS (ME)	<i>Pomacentrus vaiuli</i>	ME, SS, NS (SE)
<i>Aprion virescens</i>	SE (ME, SS, NS)	<i>Pseudocheilinus evanidus</i>	NS, SE (ME)
<i>Archamia fucata</i>	SE (ME, SS, NS)	<i>Pseudocheilinus hexataenia</i>	ME, SS (SE)
<i>Atrosalarias fuscus</i>	SE (ME, SS, NS)	<i>Pseudocheilinus octotaenia</i>	NS (ME, SS, SE)
<i>Balistapus undulatus</i>	ME, SS (SE)	<i>Pterocaesio pisang</i>	SE (ME, SS, NS)
<i>Caesio teres</i>	SS, SE (ME, NS)	<i>Pygoplites diacanthus</i>	NS, SE (ME)
<i>Caranx uelampyus</i>	SE (ME, SS, NS)	<i>Sargocentron spiniferum</i>	ME, NS (SE)
<i>Centropyge bicolor</i>	SS, NS (ME, SE)	<i>Scolopsis affinis</i>	SE (ME, SS, NS)
<i>Centropyge eibli</i>	ME (SS, NS, SE)	<i>Siganus punctatissimus</i>	SE (ME, SS)
<i>Centropyge tibicen</i>	SE (ME, SS, NS)	<i>Stegastes nigricans</i>	ME, NS (SS, SE)
<i>Centropyge vrolikii</i>	SS, SE (ME)	<i>Symodus binotatus</i>	SE (ME, SS)
<i>Cephalopholis miniata</i>	SS (ME, SE)		

Marine benthic flora and fauna of Gourdon Bay and the Dampier Peninsula in the Kimberley region of north-western Australia

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Abstract

Surveys undertaken to characterise the marine benthic habitats along the Dampier Peninsula and further south at Gourdon Bay in the Kimberley region of Western Australia were augmented with epibenthic sled sampling of soft and hard bottom habitats. This paper describes the species collected, their biomass and relative abundance for the main groups of marine macrophytes and invertebrates. Five localities were surveyed; Gourdon Bay, Quondong Point to Coulomb Point, Carnot Bay to Beagle Bay, Perpendicular Head and Packer Island. Sampling was limited to fifteen epibenthic dredge operations from a range of habitat types and was designed to target the most common habitat types and to obtain species identifications of the most important species and those which typified different habitat types. Surveys covered a total of 1,350 m² of seabed in depths between 11 and 23m. We identified 415 taxa comprising: 1 seagrass, 43 algae, 52 sponges, 30 ascidians, 10 hydroids, 14 scleractinian corals, 52 other cnidarians, 69 crustaceans, 73 molluscs and 71 echinoderms. Despite the limited nature of the sampling, a significant number of new species, range extensions and new records for Western Australia and Australia were recorded. Within the algae, one range extension (*Halimeda* cf. *cuneata* f. *digitata* not previously recorded in Western Australia) and one possible new species of *Areschougia* were recorded. Two range extensions were present in the ascidians; the solitary ascidian *Polycarpa* cf. *intonata* has previously only been recorded in Queensland and *Cnemidocarpa* cf. *radicosa* only in temperate Australian waters. There were several range extensions for the crustacea, for example, the sponge crab, *Tumidodromia dormia*, has only been recorded in Queensland. One species of holothurian of the genus *Phyllophorus* could not be identified from the literature available and may represent a new species. Similarly, a small species of the echinoid *Gymnechinus* could possibly be a new species. The collections of hydroids, hard corals, crinoids and molluscs contained no new species or range extensions. There was difficulty in identification of some groups to species level due to the status of the current taxonomic literature (e.g. Cnidaria, Porifera and ascidians) and there may be a number of new species among the material collected. Among the anthozoa, there is at least one new species of *Clromonephthea* and potentially 10 range extensions to Western Australia. *Simularia* cf. *acuta* and *Chromonephthea curvata* are both new records for Australia with both previously recorded in Indonesia only. Among the better known taxa (e.g. molluscs, echinoderms, corals), most of the taxa identified to species level have been recorded to occur throughout north-western Australia, however the diversity recorded in this study is less than other parts of the Kimberley and this is almost certainly a result of the small overall area sampled and the single method of collection utilised. The most important species on soft bottom habitats in terms of biomass was the heart urchin *Breynia desorii* (up to 326 g.m⁻²). Sponges were the dominant fauna by biomass (up to 620 g.m⁻²) on hard bottom habitats and biomass was dominated by a few large cup and massive sponge species (e.g. *Pione velans* and two unidentified *Splaciospongia*). The biomass of other filter feeders, especially ascidians (e.g. *Aplidium* cf. *crateriferum*), soft corals (e.g. *Chromonephthea* spp.), gorgonians (e.g. *Junceella fragilis* and *Dichotella gemmacea*) was also high, indicating the importance of these groups in characterising hard bottom habitats. Although low in biomass, crinoids such as *Comaster multifidus* and *Comatula pectinata* were abundant in samples that included a high biomass of other filter feeders.

Keywords: marine, benthic flora, benthic fauna, Kimberley, Gourdon Bay, Dampier Peninsula

Introduction

The marine environment of the Kimberley coastline in north-western Australia is very poorly documented, few studies having been conducted there due mainly to its remoteness (Masini *et al.* 2009). Although it is one of the few marine domains on earth largely unaffected by human impacts (Halpern *et al.* 2008), the Kimberley region is currently undergoing a revolution of increasing economic importance as a tourist destination and coastal developments of a significant scale are planned associated with exploitation of oil and gas reserves in the region. As a result of the likely increase in human usage and impacts in the region there is an imperative to gain an understanding of the distribution of marine habitats and the biodiversity these habitats support. There have been a limited number of expeditions which have documented the flora and fauna of different parts of the Kimberley coastal and marine environment including the southern Kimberley islands (Wells *et al.* 1995), the eastern Kimberley (Walker *et al.* 1996), the central Kimberley (Walker 1997). A survey covering the whole of the Kimberley region (Morgan 1992) did not include any coastal section of the Dampier Peninsula. This study is the first to report on the subtidal benthic marine flora

and fauna of Gourdon Bay and the Dampier Peninsula, areas situated in the most southerly part of the Kimberley. The specimens sampled for this study were collected during an extensive video survey of benthic habitats conducted by Fry *et al.* (2008).

Materials and Methods

Surveys were undertaken in the Kimberley region of Western Australia between 9 and 25 June 2008 at locations both north and south of Broome (Fig. 1). Five localities were surveyed; Gourdon Bay, Quondong Point to Coulomb Point, Carnot Bay to Beagle Bay, Perpendicular Head and Packer Island. Fifteen epi-benthic dredge operations were undertaken to collect benthic flora and fauna from a variety of bio-habitat types identified from underwater video footage obtained using a towed video camera. A galvanised steel frame dredge, with an opening measuring 1.5 m wide by 0.5 m high and steel meshed sides of 1.0 m depth, was towed by *FV Eylandt Pearl* at 1–1.5 knots. A nylon codend (25 mm stretched mesh) was attached to the back of the dredge to collect the sample. The operations ranged in depth from 11–23m and were from 45 to 280m in distance

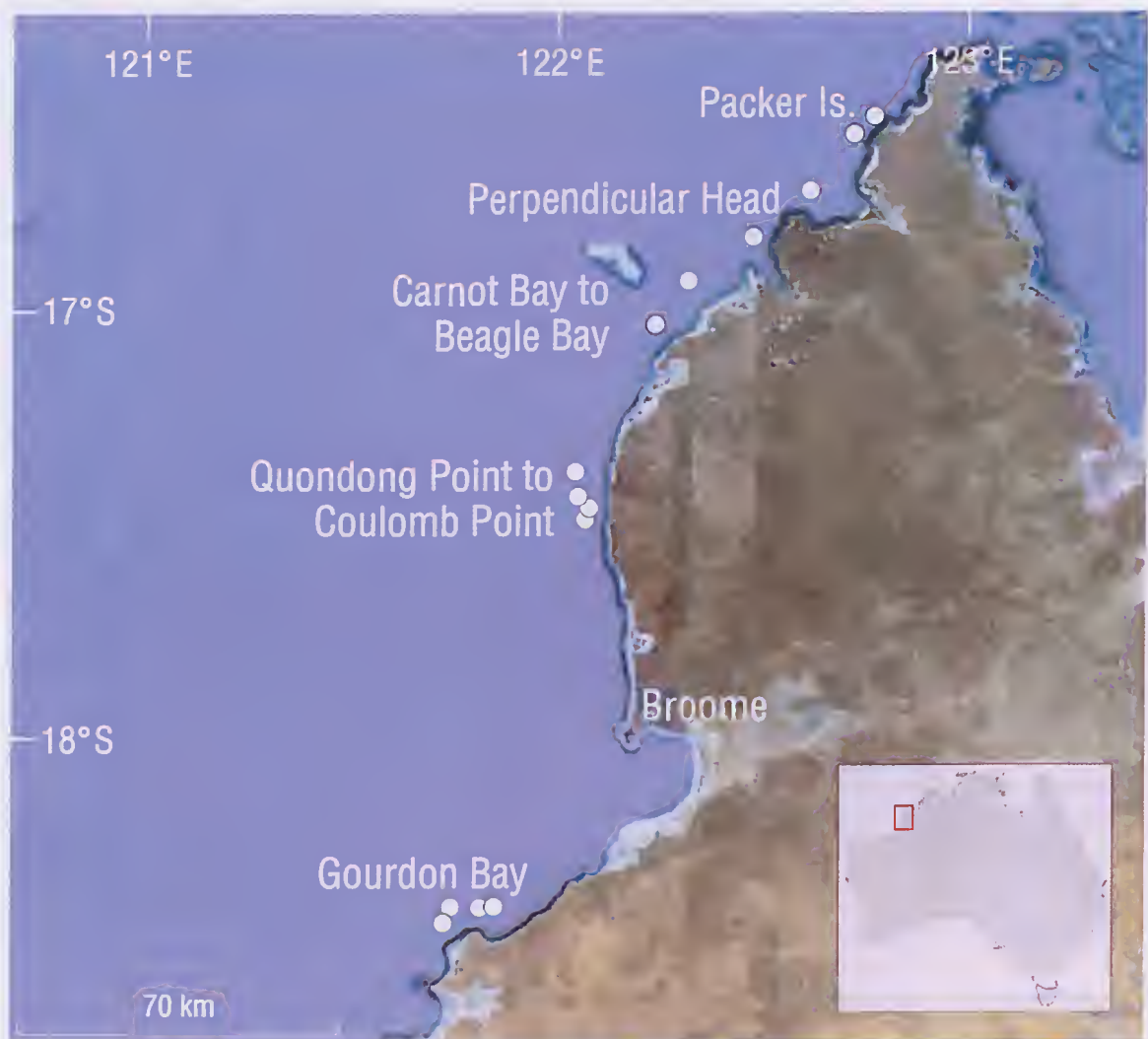


Figure 1. Location of the epi-benthic dredge towns in the Kimberley region.

Table 1

Location, date tow distance, area covered and depth of epi-benthic dredge operations

Location	Site ID	Date	Start Location	Tow Distance (m)	Area Covered (m ²)	Start Depth (m)
Gourdon Bay	2873	9/06/2008	-18.37945, 121.87140	171.4	257.1	16.8
Gourdon Bay	2898	9/06/2008	-18.38482, 121.81413	45.4	68.1	18.6
Gourdon Bay	2904	11/06/2008	-18.38633, 121.84475	280.8	421.2	14.6
Gourdon Bay	3144	9/06/2008	-18.42075, 121.76002	120.3	180.5	11.9
Quondong-Coloumb Pt	1811	17/06/2008	-17.36437, 122.06283	100.9	151.4	13.8
Quondong-Coloumb Pt	2037a	15/06/2008	-17.42017, 122.07507	86.8	130.2	11.4
Quondong-Coloumb Pt	2037b	15/06/2008	-17.42025, 122.07508	81.4	122.1	11.5
Quondong-Coloumb Pt	2132	16/06/2008	-17.45342, 122.10032	185.5	278.3	12.5
Quondong-Coloumb Pt	2200	15/06/2008	-17.47582, 122.08982	163.7	245.6	14.6
Perpendicular Head	714	20/06/2008	-16.70150, 122.62322	214.7	322.1	16.1
Perpendicular Head	1391	21/06/2008	-16.81005, 122.49002	85.7	128.6	19.2
Packer Island	278	25/06/2008	-16.52520, 122.77970	96.7	145.1	23.4
Packer Island	487	25/06/2008	-16.56675, 122.72845	151.0	226.5	16.6
Carnot Bay-Beagle Bay Line 4	5411	23/06/2008	-17.02107, 122.25362	131.1	196.7	15.7
Carnot Bay-Beagle Bay Line 5	5515	22/06/2008	-16.91575, 122.33305	117.7	176.6	12.3

depending on the density of the biohabitat targeted (Table 1). Biota collected by the dredge was sorted into species or higher level taxonomic groups, weighed (fresh wet weight to nearest gram) and photographed. Entire samples or representative subsamples of each species were retained and frozen. Some were subsequently preserved in ethanol prior to being identified to species level at a later date. Only the following groups of taxa were identified to species level (initials in brackets denote author responsible for identifications): macrophytes (JH; JP), sponges (JF), ascidians (GC), cnidarians (PA; except corals, DT and hydroids, JW), crustaceans (AH), molluscs (SS) and echinoderms (LM; except crinoids, KN).

Results

Species diversity

Among the taxonomic groups identified, we found 415 species: 43 algae, 1 seagrass, 52 sponges, 30 ascidians, 10 hydroids, 14 scleractinians, 49 alcyonarians, 3 other cnidarians, 69 crustaceans, 73 molluscs (including 37 bivalves and 33 gastropods) and 71 echinoderms (15 crinoids, 12 asteroids, 18 ophiuroids, 2 regular echinoids, 12 irregular echinoids and 12 holothuroids). A species list is provided in Table 2 along with a relative abundance based on the biomass per m² of tow area. Table 2 also denotes the new records for Australia (2) and Western Australia (13, including two algae, one ascidian, one crustacean and 10 alcyonarians) and the likely new species discovered (3, including one each of Alcyonaria, Echinoidea and Holothuroidea). It should be noted that because of the absence of previous sampling of some taxa from anywhere in north-western Australia and the poor status of taxonomic knowledge for some taxa (e.g. Porifera, Cnidaria, Crustacea and ascidians) further new species and new records are likely to be included in the samples collected which have been or will be lodged with the Western Australian Museum.

Diversity- by site

For most flora and fauna groups, the greatest diversity was recorded at either the Gourdon Bay or the Quondong to Coulomb Point locations. This is certainly the result of increased sampling effort on both hard and soft bottom types at these two locations, with 926m² and 927m² surveyed for Quondong to Coulomb Point and Gourdon Bay respectively, compared to 451m² at Perpendicular Head and 372m², at Packer Island and 373m² between Carnot Bay and Beagle Bay. Further, only soft sediment habitats were surveyed at Perpendicular Head and Packer Island and only hard bottom was sampled between Carnot Bay and Beagle Bay (Table 3). For these reasons we have not attempted to contrast the diversity between sites, however the data recording the number of species in each taxonomic group at each location is shown in Table 3.

Biomass

Sponges were the dominant fauna by biomass (up to 620 g.m⁻²) in the dredge samples where hard substrate existed (Table 4). A large number of species was collected (52) although the biomass was dominated by a few large cup and massive sponge species (e.g. *Pione velans* and two unidentified *Spherospongia*). The genus *Pione* belongs to a group of obligate bioeroders of calcium carbonate. The bulk of this species was the calcium carbonate substratum the sponge had eroded and overgrown. Non-hard coral cnidarians were also an important component of the filter feeder biomass with many species of soft coral (e.g. *Chromonephthya* spp.); and gorgonians (e.g. *Junceella fragilis* and *Dichotella gemmacea*) present in the samples. Non hard coral cnidaria comprised up to 68 g.m⁻² (Table 4). Ascidians (both colonial and solitary) were an important component of the fauna dredged at all five locations with 8 of the 15 dredge samples having ascidian biomass greater than 40 g.m⁻². Dominant ascidians in terms of biomass were *Aplidium* cf. *crateriferum* (up to 66 g.m⁻²) (Table 2). Although low in

Table 2

List of species identified from each of the five locations (GB: Gourdon Bay, QC: Quondong Point to Coulomb Point, PH: Perpendicular Head, PI: Packer Island) and BB: Carnot Bay to Beagle Bay). Relative biomass indicated as * $<0.1\text{g.m}^{-2}$, ** $0.1-1\text{g.m}^{-2}$, *** $1-10\text{g.m}^{-2}$, **** $10-100\text{g.m}^{-2}$, ***** $>100\text{g.m}^{-2}$. Species underlined are probable new species, Species with suffix (A) or (WA) are new records for Australia or Western Australia.

Location	PI	PH	QC	GB	BB	Location	PI	PH	QC	GB	BB
ALGAE						<i>Axinella</i> sp. K1			***		
<i>Amphiroa</i> sp.				*		<i>Axinella</i> sp. K2					***
<i>Areschougia</i> sp.					*	<i>Axiuella</i> sp. K3			**		
<i>Asteroumenia exanimans</i>			**	*		<i>Axiuella</i> sp. K4	***		***	****	
<i>Botryocladia leptopoda</i>			**			<i>Axinella</i> sp. K5				***	
<i>Caulerpa lentillifera</i>			**			<i>Axos flabelliformis</i>		***	***		
<i>Caulerpa racemosa</i> var. <i>lamourouxii</i>			**			<i>Callyspongia</i> sp. K1	**		***		***
<i>Caulerpa serrulata</i>				*		<i>Cinachyra</i> cf. <i>isis</i>	***	***			
<i>Champia parvula</i>			**			<i>Cinachyra</i> sp. K1			***		
<i>Chondria</i> sp.			*			<i>Cinachyrella?</i> sp. K1			***		
<i>Chondrophycus</i> sp.1					*	<i>Ciocalypa</i> sp. SS3		***	****		
<i>Chondrophycus</i> sp.2			**			<i>Clathria (Thalysias) abietina</i>			***	***	
<i>Cladophora herpestica</i>				*		<i>Clathria (Thalysias) cf. lendenfeldi</i>			**		
<i>Coelarthrum opuntia</i>			*		*	<i>Clathria cactiformis</i>	**				
<i>Cystoseira trinodis</i>					*	<i>Cliona</i> sp. K1					***
<i>Dasya</i> sp.					*	<i>Cymbastela</i> cf. <i>vespertina</i>	*	***	***		
<i>Dichotomaria marginata</i>		**		**	*	<i>Cymbastela</i> sp. K1			**		
<i>Dictyopteris woodwardia</i>					***	<i>Discodermia discifera</i>	***				***
<i>Dictyota ceylanica</i> (WA)				*		<i>Echinocalina</i> sp. K1			****		
<i>Dictyota dichotoma</i> var. <i>intricata</i>				*		<i>Echinodictyum</i> cf. <i>cancellatum</i>			***		
<i>Digenea simplex</i>					*	<i>Echinodictyum</i> cf. <i>clathrioides</i>			***		
<i>Gelidiopsis intricata</i>				*		<i>Echinodictyum</i> cf. <i>clathrioides</i>	***		***	***	
<i>Gelidiopsis scoparia</i>				*		<i>Ectyoplasia tabula</i>	**		***	***	***
<i>Gelidiopsis</i> sp.				*		<i>Halichondria</i> sp. K1				****	***
<i>Griffithsia metcalfii</i>			**			<i>Higginsia</i> sp. K1	***				
<i>Halimeda</i> cf. <i>cuneata</i> f. <i>digitata</i> (WA)			**			<i>Hippospongia</i> sp. SS1			**		
<i>Halimeda discoidea</i>			**	*		<i>Iotrochota</i> cf. <i>baculifera</i>	***			***	
<i>Halimeda opuntia</i>				*	***	<i>Luffariella</i> sp. K1			***		
<i>Halymenia floresii</i>			**		*	<i>Oceanapia</i> cf. <i>macrotoxa</i>	***		***		
<i>Hypnea cervicornis</i>					*	<i>Phakellia</i> sp. K1				****	
<i>Hypnea</i> sp.				*		<i>Piloua velans</i>				****	
<i>Jania</i> cf. <i>adhaerens</i>				*		<i>Raspailia</i> cf. <i>clathrata</i>			*		
<i>Laurencia</i> sp.				*		<i>Raspailia</i> cf. <i>uuda</i>			*		
<i>Lobophora variegata</i>				**		<i>Raspailia phakellopsis</i>				****	
<i>Peyssonnelia</i> sp.1				*		<i>Raspailia vestigifera</i>				****	
<i>Peyssonnelia</i> sp.2				*		<i>Reniochalina</i> cf. sp. 1	***				
<i>Polysiphonia</i> sp.			**			<i>Reniochalina</i> cf. <i>stalagmitis</i>	***	***	***		
<i>Sargassum</i> sp. juv.				*		<i>Reniochalina</i> sp. 1	***	***	***		
<i>Sargassum</i> sp.1			**			<i>Reniochalina</i> sp. 2	**	***	***	***	
<i>Scinaia tsinglaneensis</i>			**		*	<i>Sarcotragus</i> sp. SS8		***	***	***	****
<i>Sebdenia flabellata</i>					*	<i>Sphaciospongia</i> sp. K1		***	****	****	
<i>Solieria robusta</i>			**			<i>Sphaciospongia</i> sp. K2		***	****	****	
<i>Spirocladia barodensis</i>				*		<i>Sphaciospongia</i> sp. K3			***		
<i>Udotea flabellum</i>				*		<i>Theonella levior</i>				****	
SEAGRASS						<i>Thorecta</i> sp. K1	**		****		****
<i>Halophila decipiens</i>	**		**			<i>Thrinacophora</i> cf. <i>cervicornis</i>	*				**
PORIFERA:						<i>Trikentrion flabelliforme</i>	***		***		
<i>Aka</i> sp. K1	**					<i>Xestospongia testudinaria</i>			***		
<i>Aka</i> sp. K2		***		****		ASCIDIA: Colonial					
<i>Authothethya fromoutae</i>	***		***	***		<i>Aplidium</i> cf. <i>crateriferum</i>			***		
<i>Aplysiidae</i> sp. K1			***			<i>Aplidium</i> sp. 1			***		
<i>Arenosclera</i> sp. K1			***			<i>Aplidium</i> sp. 2	***				**

Location	PI	PH	QC	GB	BB	Location	PI	PH	QC	GB	BB
<i>Aplidium</i> sp. 3	****		***			<i>Alertigorgia orientalis</i>			**	**	
<i>Aplidium</i> sp. 4		***	***	***	***	<i>Alertigorgia</i> sp. 1				**	
<i>Aplidium</i> sp. 5			**			<i>Carijoa</i> sp. 1	**			***	
<i>Didemnum</i> sp. 1	**		***	***		<i>Chromonephthea curvata</i> (A)	**		***		***
<i>Didemnum</i> sp. 2			***	**	**	<i>Chromonephthea</i> cf. <i>curvata</i>			***		
<i>Didemnum</i> sp. 3			***			<i>Chromonephthea fruticosa</i> (WA)			***		
<i>Didemnum</i> sp. 4				***		<i>Chromonephthea ostrina</i> (WA)					***
<i>Didemnum</i> sp. 5		*		**		<i>Chromonephthea</i> sp. 1			****		
<i>Didemnum</i> sp. 6				**		<i>Chromonephthea</i> sp. 2			***		
<i>Didemnum</i> sp. 7	**		****			<i>Chromonephthea</i> sp. 3				**	
<i>Didemnum</i> sp. 8	**					<i>Chromonephthea</i> sp. 4			***		
<i>Distaplia</i> cf. <i>stylifera</i>		****		***		<i>Chromonephthea</i> sp. 5			**		
<i>Endistoma</i> sp.				***		<i>Chromonephthea</i> cf. sp. 5			**		
<i>Neptthesis fascicularis</i>	***					<i>Chromonephthea</i> sp. 6					
<i>Pseudodistoma</i> sp.1	****		****	**		<i>Chromonephthya</i> sp. 7					**
<i>Pseudodistoma</i> sp.2		****	****	****		<i>Ctenocella pectinata</i>	**	**			**
<i>Pseudodistoma</i> sp.3		****	****	****		<i>Dendronephthya</i> sp. 1				**	**
ASCIDIA: Solitary						<i>Dendronephthya</i> sp. 2	**				**
<i>Cnemidocarpa</i> cf. <i>radicosa</i>		****	*	***	**	<i>Dendronephthya</i> sp. 3	**				
<i>Phallusia obesa</i>				**		<i>Dendronephthya</i> sp. 4					**
<i>Phallusia</i> cf. <i>arabica</i>				**		<i>Dendronephthya</i> sp. 5					**
<i>Phallusia</i> cf. <i>millari</i>	***		***	**		<i>Dendronephthya</i> sp. 6					**
<i>Polycarpa</i> cf. <i>intonata</i> (WA)	****	***			****	<i>Dendronephthya</i> sp. 7					**
<i>Polycarpa</i> cf. <i>papillata</i>	**				***	<i>Dendronephthya spinosa</i>				**	
<i>Polycarpa chinensis</i>		*			***	<i>Dichotella gemmacea</i>	*	***		**	**
<i>Polycarpa clavata</i>	**	**		***		<i>Echinogorgia reticulata</i>			***		
<i>Polycarpa</i> sp.				**		<i>Echinogorgia</i> sp. A		**			
<i>Polycarpa</i> sp. 2				**		<i>Echinogorgia</i> sp. B		**			
CNIDARIA: Hydrozoa						<i>Echinogorgia</i> sp. C		**			
<i>Gymnangium longicorne</i>				***		<i>Euplexaura</i> sp. 1		**		**	
<i>Idiellana pristis</i>	***					<i>Euplexaura</i> sp. 2					**
<i>Macrorhynchia philippina</i>				*		<i>Junceella fragilis</i> (WA)	**	**	**	****	**
<i>Macrorhynchia phoenicia</i>				*		<i>Lobophytum crassum</i> (WA)			***		
<i>Plumularia badia</i>	***					<i>Melithaea albitincta</i>				***	
<i>Plumularia scabra</i>				****		<i>Melithaea</i> sp. 1					***
<i>Polypiumaria cornuta</i>	****					<i>Melithaea</i> sp. 2			***	**	
<i>Sertularella diaphana</i>	**			**		<i>Menella simplex</i>		**			
<i>Sertularella decipiens</i>	**			**		<i>Menella</i> sp. 1				**	
<i>Thyroscyphus fruticosus</i>				**		<i>Nephthea</i> sp. 1				***	
CNIDARIA: Scleractinia						<i>Nephtyigorgia kukenthalii</i>			**		
<i>Balanophyllia</i> cf. <i>generatrix</i>		**				<i>Paraplexaura</i> cf. <i>mikrodentata</i>	*	**			
<i>Cycloseris cyclolites</i>	**	*		**		<i>Paraplexaura</i> cf. <i>rigida</i>				**	
<i>Goniastrea aspera</i>				****		<i>Paraplexaura multispinosa</i>	*	**			
<i>Heterocyathus hemispherica</i>		*		*		<i>Pseudopterogorgia australiensis</i> (WA)					*
<i>Montastrea curta</i>			****			<i>Rumphella aggregata</i> (WA)				**	
<i>Moseleya latistellata</i>			****			<i>Rumphella</i> sp. 1				**	
<i>Porites australiensis</i>	***					<i>Sinularia</i> cf. <i>acuta</i> (A)			***		
<i>Porites lutea</i>				****		<i>Subergorgia suberosa</i> (WA)		**		***	*
<i>Porites solida</i>				****		CNIDARIA: Zoanthiniaria anemone					
<i>Psammodora contigua</i>	***					<i>Sphenopus marsupialis</i>		**		**	
<i>Truncatoflabellum</i> cf. <i>spheniscus</i>	**			**		CNIDARIA: Black Coral (unidentified)		***			**
<i>Tubastrea</i> sp.			***			CNIDARIA: Sea Pen					
<i>Turbinaria patula</i>			****	****		Sea Pen (unidentified)					**
<i>Turbinaria reniformis</i>		**		****		CRUSTACEA: Decapoda					
<i>Turbinaria</i> sp. (no sample)					****	<i>Achaeus brevirostris</i>	*				
CNIDARIA: Alcyonaria						<i>Actaea tuberculosa</i>				*	
<i>Acabaria</i> sp. 1	**					<i>Actumnus</i> sp. 1					

Table 2 (cont.)

Location	PI	PH	QC	GB	BB	Location	PI	PH	QC	GB	BB
<i>Actumnus</i> sp. 2		*	*		*	<i>Synalpheus tunidomanus</i>			*		
<i>Actumnus</i> sp. 3				*		<i>Thalanita annulipes</i>				*	
<i>Alpheus pareuchirus</i>	*		*	*		<i>Tumidodromia dormia</i> (WA)				**	
<i>Alpheus villosus</i>			*	*	*	<i>Upogebia darwini</i>			*		
<i>Anacinetops stimpsoni</i>	*					<i>Vellumnus labyriuthicus</i> (WA)				*	
<i>Calappa capelloni</i>			*			CRUSTACEA: Sessilia					
<i>Calappa clypeata</i>	*	*				<i>Solidobalanus socialis</i> (WA)		*			
<i>Ceratocarcinus longimanus</i>	*					<i>Striatobalanus amaryllis</i>		*			
<i>Charybdis helleri</i>			*		*	CRUSTACEA: Stomatopoda					
<i>Charybdis jaubertensis</i>				*		<i>Carinosquilla carita</i>			*		
<i>Charybdis</i> sp.				*		<i>Gonodactylaceus graphurus</i>			*	*	
<i>Cryptopodia fistulosa</i>		*		*		<i>Haptosquilla corrugata</i>				*	
<i>Dardanus imbricatus</i>		*	*			MOLLUSCA: Bivalvia					
<i>Dardanus setifer</i>			*			<i>Acrostrigma</i> cf. <i>wilsoni</i>			**		
<i>Dardanus squarrosus</i>			*			<i>Annachlamys flabellata</i>				**	
<i>Dorrippe quadridens</i>				*		<i>Antigona chemnitzii</i>					**
<i>Etisus anaglyptus</i>				*		<i>Antigona lamellaris</i>				*	**
<i>Gomezia bicornis</i>					*	<i>Barbatia</i> cf. <i>helblingii</i>			**	**	
<i>Gonatonotus pentagonus</i>	*					<i>Barbatia</i> cf. <i>lima</i>	*				
<i>Halimede ochtodes</i>			*			<i>Barbatia</i> sp.			*		
<i>Heteropanope</i> sp. 1			*	*		cf. <i>Lithophaga</i> sp. (damaged)				*	
<i>Huenia heraldica</i>			*		*	<i>Chama</i> cf. <i>fibula</i>					**
<i>Hyastenus sebae</i>			*		*	<i>Chama</i> cf. <i>lazarus</i>				***	
<i>Izanami inermis</i>	**	**		*	*	<i>Chama</i> sp.			***		
<i>Leucosia haswelli</i>	*	*				<i>Circe</i> cf. <i>scripta</i>	*				
<i>Liomera pallida</i>				*		<i>Circe scripta</i>		**			
<i>Lissoporcellana spinuligera</i>				*		<i>Dosinia</i> sp. (juv)					**
<i>Lophopilumnus globosus</i>			**			<i>Eucrassatella pulchra</i>					**
<i>Menaethius monoceros</i>				*		<i>Fulvia</i> cf. <i>australe</i>	*				
<i>Metapenaeopsis mogiensis</i>		*			*	<i>Gastrochaena</i> cf. <i>philippinensis</i>					*
<i>Metapenaeopsis sinuosa</i> (WA)	*					<i>Glycymeris</i> cf. <i>crebriliratus</i>	*				
<i>Metapenaeus</i> sp. 1	**		*			<i>Glycymeris dampierensis</i>	**	***			
<i>Micippa excavata</i>	*					<i>Glycymeris persimilis</i>				*	**
<i>Myra australis</i>	*	*				<i>Hiatella</i> cf. <i>australis</i>			**		
<i>Myra</i> cf. <i>affinis</i>		*	*			<i>Laevicardium biradiatum</i>				*	
<i>Nodolambrus nodosus</i>	*	*	*			<i>Laevicardium</i> cf. <i>biradiatum</i>					**
<i>Pachycheles sculptus</i>		*	*	*		<i>Lima vulgaris</i>	*			**	
<i>Petrolisthes militaris</i>	*		*	*	*	<i>Mactra incarnata</i>	*			*	**
<i>Philyra platycheir</i>			*			<i>Mimachlamys</i> cf. <i>funnebris</i>				**	
<i>Pilodius</i> sp. 1					*	<i>Mimachlamys funnebris</i>				*	
<i>Pilumnopus</i> sp. 1	*	*	*	*	*	<i>Modiolus phillipinarum</i>	*				
<i>Pilumnopus</i> sp. 2			*	*		<i>Paphia semirugata</i>	*				
<i>Pilumnus pulcher</i>			**	**		<i>Pinctada maxima</i>	***				
<i>Pilumnus vespertilio</i>			*	*		<i>Pinna deltodes</i>				**	
<i>Polyonyx biunguiculatus</i>				*		<i>Pinna</i> sp. (juv).				*	
<i>Polyonyx triunguiculatus</i>			*			<i>Placamen tiara</i>			*		
<i>Portunus curvipes</i>		*				<i>Pteria</i> cf. <i>lata</i>				**	
<i>Portunus rubromarginatus</i>	**		*			<i>Pteria penguin</i>				***	
<i>Pseudolambrus harpax</i>	*					<i>Semele</i> cf. <i>zebuensis</i>	*				
<i>Pseudopaguristes</i> sp. 1			*			<i>Spondylus</i> cf. <i>violascens</i>				**	
<i>Schizophris dama</i>	*		*	**	**	<i>Spondylus victoriac</i>	**			*	
<i>Seulocia laevimana</i>			*			<i>Trisidos senitorta</i>	*				
<i>Stimodromia lateralis</i>				*		MOLLUSCA: Cephalopoda					
<i>Synalpheus comatularum</i>				*	**	<i>Sepia papuensis</i>				*	
<i>Synalpheus pococki</i>			**			<i>Octopus</i> sp. A				*	
<i>Synalpheus stimpsoni</i>			*	*		<i>Octopus</i> sp. B	**				

Location	PI	PH	QC	GB	BB	Location	PI	PH	QC	GB	BB
MOLLUSCA: Gastropoda						<i>Astropecten zebra</i>	**	**	*	**	
<i>Ancillista muscae</i>				**		<i>Echinaster varicolor</i>				**	
<i>Cantharus erythrostomus</i>				**	*	<i>Goniodiscaster acanthodes</i>			**		
cf. <i>Calthalotia</i> sp.			*			<i>Gymnanthena globigera</i>				**	
<i>Chicoreus banksii</i>					**	<i>Metrodora subulata</i>	**			*	
<i>Clanculus atropurpureus</i>				*		<i>Nepanthia belcheri</i>				**	**
<i>Clanculus bicarinatus</i>			*		*	<i>Pseudoreaster obtusangulus</i>			***		
<i>Conus cf. reductaspiralis</i>			*			<i>Stellaster childreni</i>	**	**		***	
<i>Conus novae-hollandiae</i>			*			ECHINODERMATA: Ophiuroidea					
<i>Cronia avellana</i>			**	**	**	<i>Dictenophinra stellata</i>			*		
<i>Cymatium cf. vespacinum</i>			*			<i>Macrophiothrix caenosa</i>				*	
<i>Cypraea subviridis dorsalis</i>			*			<i>Macrophiothrix callizona</i>				*	
<i>Diadora cf. singaporensis</i>			*			<i>Macrophiothrix cf. megapoma</i>					*
<i>Engina cf. curtisiana</i>				*		<i>Macrophiothrix megapoma</i>			**	**	*
Fasciariidae			*			<i>Macrophiothrix microplax</i>				*	
<i>Gyrineum cf. lacunatum</i>			*			<i>Ophiactis savignyi</i>				*	
<i>Herpetopoma atrata</i>		*		*		<i>Ophiochasma stellata</i>		*		*	
<i>Hexaplex stainforthi</i>			**	**		<i>Ophiocoris cincta</i>				*	
<i>Latirus</i> sp.				*		<i>Ophiomaza cacaotica</i>		*	*	*	***
<i>Morula?</i> sp.				*		<i>Ophiothrix (Keystonea) martensi</i>				*	
<i>Murex acanthostephes</i>	*		**			<i>Ophiothrix (Keystonea) smaragdina</i>		*	*	*	*
<i>Natica euzona</i>						<i>Ophiothrix (Placophiothrix) lineocerulea</i>			*	**	*
<i>Phos senticosus</i>	*		*			<i>Ophiothrix (Placophiothrix) striolata</i>				*	
<i>Scutus nnguis</i>						<i>Ophiothrix ciliaris</i>	*	*	*	**	*
<i>Strombus campbelli</i>	*			*		<i>Ophiothrix ciliaris/exigna</i>		*	*		
<i>Syrinx aruanus</i>	**					<i>Ophiolurix exigna</i>		*	*		
<i>Tectus fenestratus</i>						<i>Ophiothrix sp.1</i>			*	*	
<i>Thais echinata</i>			*	**		ECHINODERMATA: Echinoidea					
<i>Turris cf. crispa</i>			*	*		<i>Brynia desorii</i>	***	****	*****	****	***
<i>Vexillum vulpeculum</i>	*	*				<i>Brissopsis</i> sp.					***
MOLLUSCA: Opisthobranchia						cf. <i>Gymnechinus</i> sp.				*	**
<i>Bornella anguilla</i>					**	<i>Clypeaster (Coronanthus) telurus</i>					**
<i>Moridilla brockii</i>			*		**	<i>Clypeaster latissimus</i>				*	
<i>Nembrotha purpureolineata</i>	*		**			<i>Clypeaster (Stolonoclypsus) virescens</i>		**		**	
<i>Platydoris</i> sp.			*			<i>Echinolampas ovate</i>					***
ECHINODERMATA: Crinoidea						<i>Lovenia elongate</i>				****	***
<i>Capillaster multiradiata</i>	*				***	<i>Peronella lesneuri</i>	**	**	**	***	
<i>Clarkcomanthus littoralis</i>		*	**		*	<i>Peronella macroproctes</i>	*	**			*
<i>Clarkcomanthus luteofuscum</i>				*		<i>Peronella orbicularis</i>	*	**			
<i>Comanthus wahlbergii</i>				***		<i>Peronella tuberculata</i>	*		*		
<i>Comaster multifidus</i>			***	***	***	<i>Prionocidaris bispinosa</i>	***			**	**
<i>Comaster schlegelii</i>	*		**	**	**	<i>Temnopleurus alexandri</i>				**	**
<i>Comatella maculata</i>				**	***	ECHINODERMATA: Holothuroidea					
<i>Comatula pectinata</i>	*	***	**	***	***	<i>Actinocucumis typica</i>					**
<i>Comatula rotalaria</i>	**	***		***		<i>Cercodemas anceps</i>	**	*	**	*	
<i>Heterometra crenulata</i>	***	**				<i>Cladolabes schmeltzii</i>			***		
<i>Heterometra sarae</i>				*		<i>Colochirus crassus</i>			**		
<i>Zygometa cf. comata</i>				*		<i>Colochirus quadrangularis</i>			***	***	**
<i>Zygometa comata</i>	*			*	*	<i>Holothuria (Halodeima) atra</i>					**
<i>Zygometa microdiscus</i>				*		<i>Holothuria (Theelothuria) michaelsoni</i>	**			*	
<i>Zygometa punctata</i>			*			<i>Phyllophorus (Urodemella) proteus</i>					***
ECHINODERMATA: Asteroidea						<i>Phyllophorus</i> sp.					**
<i>Anthenea conjugens</i>			***			cf. <i>Phyllophorus</i> sp.					*
<i>Astropecten monacanthus</i>			*	*		<i>Stolus buccalis</i>				***	*
<i>Astropecten vappa</i>	**					<i>Synaptula recta</i>			***		***
<i>Astropecten velitaris</i>			**	**							

Table 3

Summary of the dredge area and number of species within functional groups recorded in each epi-benthic dredge tow (PI – Packer Island; PH – Perpendicular Head; QC – Quondong Point to Coulomb Point; GB – Gourdon Bay; BB – Carnot Bay to Beagle Bay).

Location	Transect #	Habitat	Area Sampled (m ²)	Algae	Sea-grass	Pori-fera	Asci-dia	Cnid-aria	Crust-acea	Moll-usca	Echino-dermata
PI	278	Soft	145	0	0	2	4	5	10	12	13
PI	487	Soft	227	0	1	23	9	14	11	9	9
PH	714	Soft	322	0	0	0	3	2	9	2	11
PH	1391	Soft	129	1	0	11	6	16	7	3	9
QC	1811	Soft	151	13	1	26	5	6	14	12	14
QC	2037a	Hard	130	0	0	0	0	0	4	1	8
QC	2037b	Hard	122	5	1	6	6	3	6	5	10
QC	2132	Soft	278	4	1	20	6	13	18	9	12
QC	2200	Soft	245	0	0	0	2	0	7	2	6
GB	2873	Soft	257	0	0	3	2	2	10	7	28
GB	2898	Hard	68	2	0	9	3	7	11	2	15
GB	2904	Soft	421	1	0	0	2	4	2	9	19
GB	3144	Hard	181	18	0	11	12	20	16	15	16
BB	5411	Hard	197	10	0	4	9	14	4	6	9
BB	5515	Hard	177	6	0	8	3	11	10	12	23

biomass, crinoids such as *Comaster multifidus* and *Comatula pectinata* (up to 18 g.m⁻²) were abundant in samples that included a high biomass of other filter feeders (Table 4).

Benthic primary producers had a low biomass in the samples collected. Few hard corals were caught with the most dominant species being *Turbinaria patula* and *T. reniformis*. The highest coral biomass recorded was at Gourdon Bay (up to 426 g.m⁻²). Other areas of high coral cover were observed in the surveys conducted by Fry *et al.* (2008) however it is thought the type of dredge used did not adequately sample some massive and encrusting growth forms efficiently. In addition no hard bottom was sampled in the Perpendicular Head and Packer Island locations. Algae and seagrass had low biomass at all sites, with the exception of the site nearest Carnot Bay (5411) where algae comprised about 13 g.m⁻² (Table 4).

Echinoderms were well represented in the samples and comprised the highest biomass of any taxa on soft bottom habitats. Three of the dredge tows at Gourdon Bay and Quondong-Coulumb (2200, 2873, and 2904) caught a large number of the heart urchins (*Breyenia desorii* and *Lovenia elongata*) with a biomass of between 55 and 326 g.m⁻² (Table 4). The biomass of asteroids was highest on soft sediment habitats (up to 3.36 g.m⁻²) of which most was *Stellaster childreni* but few other types of organisms were caught in the dredge at these transects as the substratum was observed to be nearly 100% bioturbated fine sand or bare coarse sand. Molluscs were common in the samples but made up a low biomass due to their small size. The sampling gear would have been ineffective in sampling small molluscs as a result of the 25mm mesh size. The biomass of other taxa not included in the taxonomic analysis is included in Table 4, the highest biomass of which was bryozoa (up to 294 g.m⁻²) at Gourdon Bay.

Discussion

Previous surveys of the Kimberley region (Wells *et al.* 1995; Walker *et al.* 1996; Walker 1997; Morgan 1992) have not covered the Dampier Peninsula and Gourdon Bay regions so this study contributes to a gap in our knowledge of the biodiversity of an important part of the Kimberley coast where development pressure is expected to increase. In addition, previous surveys have not examined some of the taxonomic groups covered here (e.g. non-coral cnidarians, porifera and ascidians). These filter feeder taxa dominate much of the biomass of benthic habitats in this region (e.g., Table 4 this study; Fry *et al.* 2008). Elsewhere in Western Australia, where more extensive studies have been undertaken, such as in the south-west (McEnulty *et al.* in press) and in the north-west at Ningaloo (Fromont unpublished) and the Dampier archipelago (Fromont *et al.* 2006), filter feeders such as sponges also dominate benthic animal biomass. Further research in the Kimberley is likely to reveal that filter feeders play an important role in the ecosystem and thus these groups warrant more attention in biodiversity surveys in the region. Below we discuss the findings of this study for each of the taxonomic groups examined.

Algae and Seagrass

A total of 43 species of macroalgae from 22 families were identified. The greatest diversity of marine flora was recorded at the Quondong to Coulomb Point location (24 species), followed by Gourdon Bay (21 species). *Halophila decipiens* was the only seagrass species collected. This species was identified in four tow samples from Packer Island and Quondong-Coulumb.

Of the 43 species of algae, 14 could not be identified further than genus level, although they were recognised as discrete entities. In some instances (e.g. *Laurencia* sp.,

Chondrophyucus sp.1 and sp.2) this was due to specimens being infertile, as reproductive material is necessary to confirm the placement of such species. Certain other species (e.g. *Peyssonnelia* sp.1 and sp.2) require a detailed examination of the internal structure, aided by appropriate taxonomic keys. Specimens of some smaller species (e.g. *Hypnea* sp., *Dasya* sp., *Polysiphonia* sp.) were damaged by the freezing and thawing process and could not be identified beyond genus level.

Among the green algae (Chlorophyta), *Caulerpa* and *Halimeda* were most diverse with three species from each genus collected. One species of *Halimeda* had a distinctive appearance of large lower segments giving rise to numerous chains of narrow, elongated segments and was assigned to *Halimeda* cf. *cuneata* f. *digitata*. This species has not been recorded in WA although more detailed internal examination and/or genetic sequencing would be required to confirm its placement within this species.

The brown algae (Phaeophyceae) were represented by seven species belonging to the families Dictyotaceae and Sargassaceae. Several juvenile *Sargassum* plants (*Sargassum* sp.) were also collected in the samples. These juvenile plants may have been different species, but due to their small size (to ca. 2 cm high) could not be identified further. A large, reproductively mature *Sargassum* specimen (*Sargassum* sp.1) could not be identified to species level due to the lack of detailed taxonomic information available for *Sargassum* occurring in north-west Australia. The taxonomy of the north-west *Sargassum* species is currently under investigation (Dixon & Huisman 2010) and the voucher specimen from the current survey will be revisited at a later date. The distribution of *Dictyota ceylanica* in Western Australia is unknown at present, however it is reported to occur worldwide in tropical and subtropical waters (Abbott and Huisman, 2004; Huisman *et al.*, 2007).

The red algae were the most diverse group among the collection, with 28 species recorded. Families were represented by only 1–3 species, with the exception of the Rhodomelaceae with seven species. The widely distributed but rarely collected (Huisman, 2000) *Asteromenia exanimans* was identified from two tow samples from Quondong-Coulumb and Gourdon Bay. A specimen identified as *Areschongia* sp. may possibly be a new species, but fertile (reproductive) material or genetic sequencing would be required to confirm this. Within Western Australia, *Gelidiopsis scoparia* has currently only been reported from Ningaloo and Dampier Archipelago.

The marine flora of north-western Australia is relatively poorly known and a comprehensive flora list has yet to be published for the region (Huisman *et al.*, 2009). Huisman and Borowitzka (2003) reported 210 species from the Dampier Archipelago, while an earlier survey of the eastern Kimberley region by Walker (1996) recorded 93 species from the intertidal zone alone. A survey of the marine flora of the region's offshore atolls (Rowley Shoals, Scott Reef and Seringapatam Reef, Huisman *et al.* 2009) recorded 210 species, and gave an estimate of the north-western Australian flora as > 350 species. The present study recorded 44 species of macroalgae and seagrass from the dredge tows in waters of between 11.4 and 23.4 depth. The lower species diversity in this study was due to this limited depth range, the method of collection and the targeted nature

of the sampling design. A detailed examination of microscopic and epiphytic algae would have increased the number of species identified, but would still not fully account for the apparent low biodiversity. For example, the genus *Sargassum* in particular appears to be under-represented in the collection. This algae genus is among the most common macroalgae in tropical regions (Huisman 2000), yet only one adult species and several unidentifiable juveniles were collected. Macroalgae with certain morphologies, e.g. small, delicate or fragile thalli, are also likely to be under-represented in the collection. This is also likely attributed to the collection method and dredging equipment used. Walker & Prince (1987) visited 4 sites within the region of our study and recorded a total of 6 species of seagrass however their surveys were limited to intertidal areas.

Porifera

A total of 154 sponge specimens were examined for further identification. Of these, there were 52 species of Demospongiae from 18 families identified. A number of other sponge samples were caught in the dredges but not retained. These were only identified to the broad Porifera group. Of the identified taxa, the greatest sponge diversity was recorded at the Quondong to Coulomb Point location (52 species). This was followed by the Packer Island location (25 species) and Gourdon Bay location (23 species), with only 11 species recorded at the Perpendicular Head location and nine from the Carnot Bay to Beagle Bay location.

Due to complications with historic literature and the current classification for the Porifera group, just over half of the 52 species (29) were not identified to species. These have been identified as discrete species and given a species number which is consistent with all Porifera identification from the Western Australian Museum. It was therefore not possible to determine if these unidentified taxa have been previously described or are new species. Of the 23 species that were identified, nine species have been previously reported from Western Australia and the Northern Territory. A further seven species appear to be endemic to the west coast of Australia. Most of these species have previously been reported from north Western Australia, around the Dampier Archipelago due to the significant amount of sponge research that has been undertaken in that area. Three additional species are known to occur in tropical Australia and four are widespread Indo-Pacific. This suggests that the Kimberley has a few Indo-Pacific sponge species but the majority are more restricted in their distribution to the north and northwest of Australia, or are Western Australian endemics.

North Western Australia is known to have a high diversity of sponges. Hooper *et al.* (2002) considered the North-West Shelf of Western Australia to be one of three sponge biodiversity hotspots in Australia, containing more than 600 species. Bergquist and Kelly-Borges (1995) found more species of the Indo-Pacific family Ianthellidae in the Dampierian province (mid-west to north-west Australia), with two apparently endemic species, than anywhere else in the Indo-Pacific region. Furthermore, a study in the Dampier Archipelago recorded 275 sponge species collected by both dredge and diver expeditions (Jones 2004). However, the sponge fauna of the coastal

Table 4

Biomass (g.m⁻²) of benthic catch from each dredge operation within the five locations (GB: Gourdon Bay, QC: Quondong Point to Coulomb Point, PH: Perpendicular Head, PI: Packer Island and BB: Carnot Bay to Beagle Bay).

	PI	PH	PH	QC	QC	QC	QC	GB	GB	GB	GB	BB	BB
Transect Number	278	487	714	1391	1811	2037a	2037b	2132	2873	2898	2904	3144	5411
Area Sampled (m ²)	145	227	322	129	151	130	122	278	257	68	421	181	197
Algae												0.10	
<i>Halimeda</i>													
Other Chlorophytes											0.01		2.03
Chlorophyte/Rhodophyte													
Mix				0.28	2.58		<0.01	0.57		0.53		0.93	6.53
Phaeophyte							0.01	0.29		0.26		0.09	3.38
<i>Halophila</i>		0.18			0.19								0.01
Hydrozoa	15.27	2.69		4.46						0.53		0.20	18.37
Anemone				0.31									1.81
Soft corals					41.64			65.94		0.71		3.26	6.27
Gorgonians (branched)		0.95	0.34	20.60	2.18		1.64	2.34		0.85		11.88	1.04
Gorg. (unbranched)		0.19		3.65	4.76			0.54		3.03		16.93	0.79
Hard Coral		5.76	0.01	0.34	38.34		26.21			426.07		199.43	58.30
Solitary Coral									0.76		0.31		
Unspecified		4.30			32.06					4.35		5.31	0.63
Demospongiae													3.05
Cup					165.24			58.57				37.73	40.51
Massive					227.44			39.17		251.08		369.52	88.64
Mixed				37.35						226.40		67.22	
Unspecified	0.85	77.06	0.11		229.82		126.55	71.62					362.49
Decapoda	0.37		0.25	0.12	1.12	0.20	0.25	0.58	0.90	1.18	0.04	0.31	0.16
Unspecified	0.73	0.57											0.11

Echinodermata	Astroidea	0.68	0.12	1.32			1.65	0.24	1.21	0.26	3.36	1.09		0.74
	Echinoidea	7.76	24.22	0.34	0.97	0.23	0.17	325.91	92.62	0.97	55.70		0.81	9.38
	Holothuroidea	0.21	0.12	0.13	0.13	0.05	1.05	0.12	0.06	6.20	0.03		1.87	5.40
	Crinoidea	3.93	3.26	0.16	3.79	1.07	0.13	0.28	5.11	18.19	3.06	1.16	7.45	1.47
	Ophiuroidea		0.09	0.19	0.25	0.08	0.08	0.21	0.71	0.94	0.08	0.66		0.18
	Unspecified	4.12	0.59							17.82				
Mollusca	Gastropoda		0.09	0.36	0.70		0.03	0.27	0.01	0.29	0.15	0.51	0.71	
	Bivalvia		0.06	1.52	9.52		0.23	0.36	<0.01	0.29	0.37	12.28	0.31	2.19
	Cephalopoda										0.04			
	Octopoda											0.03		
	Opisthobranchia				0.40	0.00		0.01					0.16	0.11
Mollusca	Unspecified	81.21	12.98						0.10					0.11
Ascidia	Solitary Tunicates		0.09	1.76			1.64	0.07	0.49		0.83	17.31	30.24	3.85
	Colonial Tunicates	77.21	42.93	118.62	80.04		49.47	91.63	1.08	99.55	0.10	83.96		
	Didemnidae									5.44		2.14		
Bryozoa	Unspecified	1.38	0.36	0.06	0.87					293.84		1.35	1.95	1.83
Annelida	Polychaeta		0.02				0.49					0.02		0.26
Nemerteans	Unspecified				0.08									
Sipuncula	Unspecified								0.51					
Teleosts	Unspecified	1.86	0.59	0.75	0.62	1.31	1.64	0.18	0.24	0.73	0.38	0.04	0.10	0.23
Biol. Conglomerates	Excl Sponge		3.91		17.66	13.10								6.39
	Incl Sponge			165.24	92.13	343.97								
Other	Rocks / Rubble			147.73					116.67	550.95	49.85	421.02	864.77	116.09
Total Catch		195	155	30	340	113	567	338	327	1893	132	1249	1149	519

Kimberley region of Australia has been poorly studied and requires a significant amount of research. The collection of 52 species does not appear to reflect the extent of the sponge biodiversity expected within the Kimberley region but does give an indication of the high sponge diversity recorded from this limited area and the low number of dredge tows which targeted hard bottom habitats. That the diversity and biomass of sponges in the study region should be high, is not surprising and is consistent with other tropical locations along the Western Australian coast, such as Ningaloo Reef (Fromont pers. obs.) and the Dampier Archipelago (Fromont *et al.* 2006). Although it is likely that some sponge species in the area are new records or species for Western Australia, confirmation must await detailed taxonomic assessment. Nonetheless the sponge collection also contained examples of species that, based on gross morphology and skeletal characters, are widely distributed along the Western Australian coast and were also collected in deeper waters off Ningaloo (Fromont unpublished).

Asidiacea

Thirty separate taxa of ascidians were sampled but only eleven of these species could be identified to species level, in part due to freezing before preservation. The remainder were identified to genus. Nineteen species of ascidians were identified from each of the Quondong to Coulomb Point and Gourdon Bay locations. Thirteen species were recorded at the Packer Island location and nine at the Perpendicular Head and Carnot Bay to Beagle Bay locations. Ascidians can be divided into two distinct morphologies, 'solitary species' where there is only a single individual or 'colonial species' where there are numerous, often small, individuals within a common colonial body or test. There were 20 species from six families that were colonial forms and 10 species from two families that were solitary forms. Colonial species were relatively abundant and three genera; *Aplidium*, *Didemnum* and *Pseudodistoma* represented the majority of the samples. These comprised six species of *Aplidium*, eight species of *Didemnum* and three species of *Pseudodistoma*. There was also one species representing each of the *Distaplia*, *Eudistoma* and *Neptthesis* genera. *Aplidium*, *Didemnum* and *Pseudodistoma* are widespread throughout Australia and species from these genera are found in most tropical and temperate waters (Kott 1990, 1992). Of the less common colonials, *Neptthesis fascicularis* has previously been recorded across tropical Australia, including at Broome and *Distaplia styliifera* has a wide distribution through temperate and tropical Australia (Kott 1990, 1992).

The most common solitary ascidians were from the genera *Polycarpa* (six species) and *Phallusia* (three species). The most abundant of the solitary ascidians was *Polycarpa* cf. *intonata*, a small (3–5cm) round species heavily encrusted with sand and found buried in sandy sediments. This species has previously only been recorded in Queensland (Kott 1985). *Polycarpa* and *Phallusia* are common throughout Australia in both tropical and temperate waters. *Polycarpa chinensis* was also common in the samples and has a wide distribution including the Dampier Archipelago, Cockburn Sound, Queensland, Victoria, Vietnam and China and *Polycarpa* cf. *papillata* which also has a wide distribution from the Dampier Archipelago, Shark Bay, Queensland, Victoria,

the Arafura Sea, Indonesia and Ceylon (Kott 1985). Of the less common genera in the samples *Cnemidocarpa* closely resembling *C. radicata* was recorded, which has previously only been observed in temperate Australian waters (Kott 1985).

The species present in this collection indicate that both sandy sediment and some harder substrates were sampled with the dredge as taxa of both communities were represented. The ascidian fauna of the Kimberley region is not well known and there are no other collections known from this area. It is therefore difficult to make any direct comparisons of the expected diversity of species or to their known distributions in relation to other studies.

Cnidaria – Hydrozoa

Hydroids collected comprised ten species, from four families. Five of the species were collected at the Gourdon Bay location, four at the Packer Island location and one at each of the stations between Carnot Bay and Beagle Bay. These species form large colonies attached to shallow-water reef and rubble bottom and are adapted to fairly turbid conditions and mild to strong current flows. The samples comprised a suite of common tropical species with known distributions across much of tropical Australia (see Watson 2000). Some of these species have also been recorded from Indonesia and are circumglobal-tropical in distribution. No previous surveys of the Kimberley- Pilbara region have reported species compositions for the hydroids. However, diversity may be considered low, reflecting low sampling frequency at each site and coarse sampling methods by dredging rather than more selective scuba diving.

Cnidaria – Anthozoa – Scleractinia

Hard coral samples collected comprised 6 families, 11 genera and 14 species. Eight species were collected at the Gourdon Bay location and four species at each of the other four locations. Azooxanthellate scleractinian colonies were the most abundant group, comprising 44 of the 58 colonies identified. In comparison, colonies of zooxanthellate scleractinian species were less abundant (14 of the 58 colonies) but were more diverse in species (9 of the 14 species identified). The most abundant azooxanthellate species was *Cycloseris cyclolites* (31 colonies), while the two most abundant zooxanthellate species were *Turbinaria reniformis* (3 colonies) and *Turbinaria patula* (3 colonies). Eight of the 14 species recorded were represented by only one colony. The most represented family was Dendrophyllidae (5 species) followed by Faviidae (3 species) and Poritidae (3 species). In dredge samples where hard corals were recorded, diversity was generally low with usually only 2 or 3 species present. All 14 species of corals identified have widespread distributions and are common throughout the Indo-Pacific region (Cairns 1998; Veron & Marsh 1988) and north-western Australia, (Veron & Marsh 1988). None of these new records represent range extensions.

However, very few coral collections exist for the inshore waters of the Kimberley coast with accounts of hard coral diversity being available from only a limited number of studies. Veron and Marsh (1988) stated that 102 species of hard corals have been recorded from the

Kimberley coast and nearshore reefs; while more recently, Cairns (1998) recorded 87 species of azooxanthellate hard coral species from north-western Australian waters. However a recent survey by Griffith (2004) increased the number of hard coral species identified from the nearby Dampier Archipelago to 229.

Limited coral surveys conducted at Broome (15 species) and the Lacepede Islands (10 species) (Veron & Marsh 1988) suggest the species diversity observed in this study (14 species) may be representative of the local area. However, the low species diversity observed in this study may reflect low sampling frequency, limited depth range (11–23 m) or inadequate sampling in habitats considered favourable for the proliferation of hard corals (hard substrate).

Cnidaria – other Anthozoans

Forty-eight (48) species of other anthozoans from 11 families were sampled. Seventeen of these species were collected at the Gourdon Bay location, 16 at the Quondong to Coulomb Point location, 11 at the Perpendicular Head location and 10 at the Packer Island location. Of the 48 species only 21 were able to be identified to species level. The remainder were identified to genus level. The nomenclature for these genera needs revision as the current classification literature does not account for the high level of intra-colony and intra-species variability. It was therefore not possible to determine whether these anthozoan species constitute new previously undescribed species. There is, however, at least one new species of *Chromoneplithea*.

There are potentially 10 species collected that now show range extensions into Western Australian waters (see Table 2). However, most are known to occur in other tropical coastal areas of northern Australia. Exceptions are *Siulularia* cf. *acuta* and *Chromoneplithea curvata* which have both only been previously recorded only in Indonesia. Further, the only published record of *Paraplexaura* cf. *rigida* is from Shark Bay, WA. Nephtheidae and Plexauridae were well represented with 19 and 13 species from each family, respectively. The remaining nine families had less than four species present in the dredge samples, with five of these only having one species. As there is no other published literature on non-scleractinian cnidaria diversity in the Kimberley region, no conclusions can be made about the representativeness of this collection to expected species diversity of the region.

Crustacea

A total of 69 crustacean species from 21 families were identified from the dredge samples. The greatest crustacean diversity was recorded at the Quondong to Coulomb Point location (49 species), followed by the Gourdon Bay location (39 species), Packer Island (21 species) and Perpendicular Head (16 species). Of the 69 total species, ten could not be confidently identified to species level using current descriptions in the literature – six Pilumnidae hairy crabs (three *Actumnus*, two *Pilumnopus*, one *Heteropanope*), one Portunidae swimming crab (*Charybdis*), one Xanthidae stone crab (*Pilodius*), one Diogenidae hermit crab (*Psuedopaguristes*) and one Penaeidae prawn (*Metapenaeus*). Most of the specimens collected belong to the order Decapoda, which

contains the most familiar groups of crustaceans – the Anomura (Hermit crabs and false crabs) Brachyura (crabs), Caridea (shrimp), Gebiidea (ghost shrimp and mud lobsters), Penaeoidea (prawns).

The anomuran species present in this collection comprise only a small component of that group's diversity in tropical Australian waters, with only the Diogenidae (left-handed' hermit crabs) and Porcellanidae (porcelain crabs) represented.

The major families of the Brachyura were represented by at least one species each. The Pilumnidae was the most common brachyuran family in the collection, represented by 13 species. This family is very diverse and the species are very difficult to identify owing to a lack of comprehensive systematic accounts, resulting in a high proportion of specimens identified to morphospecies. The Xanthid crabs are typically the most speciose decapod family in areas where coral rubble/reef systems are present (e.g. Hewitt 2004; Hewitt *et al.* 2009), which contrasts with the four taxa present in the current collection. The two species of the pilumnid subfamily Eumedoninae identified, *Ceratacarinus longimanus* and *Gonatonotus pentagonus*, are notable for their lifestyle as obligate commensals on crinoids and echinoids respectively. Such echinoderm associations are a common feature of this crustacean subfamily (Davie 2002b).

The only species in the Caridea group to be recorded from the dredge samples was the snapping shrimps of the family Alpheidae. Of these, two species are known to form associations with crinoids, *Synalpheus comatularum* and *S. stimpsoni*. A single bopyrid isopod was found as a parasite on a specimen of *Alpheus parruchirus*.

There was also only one gebiid species collected, *Upogebia darwini*. Like other members of its group, this species burrows in soft sediments. However, it has also been found in close association with sponges. One of the specimens of *U. darwini* was found to be host to a rhizocephalan barnacle, an aberrant group which parasitises other crustaceans.

The non-decapod specimens identified belong to the Cirripedia (barnacles) and Stomatopoda (mantis shrimp) orders. Apart from the unidentified rhizocephalan, only two other specimens of barnacles were present, both being attached to the same gastropod shell inhabited by the hermit crab *Dardanus imbricatus*. The three species of stomatopods identified, *Carinosquilla carita*, *Haptosquilla corrugata* and *Gonodactylaceus graphurus* are common in tropical Australian waters (Ahyong 2001).

The majority of crustacean species recorded in the dredge samples have an extensive tropical Indo-West Pacific distribution (78%), in that most can be found across northern Australia and in south-east Asian waters. Only three species – *Dardanus squarrosus*, *Portunus curvidens* and *Thalamita annulipes* – are Western Australian endemics. Four of the species represented have not been collected during previous surveys in the region with *Metapenaeopsis sinuosa*, *Vellumnus labyrinthicus*, *Solidobalanus socialis* and *Tumidodromia dormia* newly recorded from Western Australian fauna (decapods not listed in Davie 2002a,b). This trend in the biogeographical affinity of decapod crustaceans is consistent with previous surveys of tropical Western

Australia (Morgan 1990; Hewitt 2004; Hewitt *et al.* 2009). The Kimberley subtidal decapod crustacean fauna can be summarised as being dominated by wide ranging Indo-Pacific species, with a low number of species being endemics to Australia. The majority of the species collected can be considered as exclusively tropical species, with only a few, such as *Stindrowia lateralis*, having a significant temperate distributional range (Davie 2002b).

While the decapod collection from this survey is quite diverse, there are several major groups not represented. No members of the Infraorder Palinura (crayfish, slipper lobsters) were collected although the shallow waters sampled should have been an ideal habitat for them. Specimens of the family Alpheidae were the only members of the Caridea (shrimp) collected, although the Caridea is the second largest infraorder of decapods, with approximately 600 species recorded from Australian waters (Davie 2002a).

Knowledge of the crustacean fauna of north Western Australia is patchy, but several expeditions have been carried out along the coasts of the central and northern Kimberley region focussing on the decapod crustacean fauna (e.g. Morgan 1992; Davie & Short 1995, 1996; Hewitt 1997). The records of the Western Australian Museum (Hosie unpublished) indicate that at least 400 species from 50 families of decapod and stomatopod crustaceans have been found in the Kimberley region as a whole and a similar number have been recorded from the Dampier Archipelago area in the Pilbara region (Hewitt 2004). Overall, the missing diversity reflects the limited range of habitat types surveyed and the limited depth range sampled. In addition it is most likely that species or groups under-represented in the samples are highly cryptic, commensal or otherwise associated with habitats that are not adequately sampled by dredge methods. The carideans in particular have a high rate of symbiotic relationships (Davie 2002a). Further species of crustaceans are perhaps still attached to their associated hosts. An increase in sampling effort and utilising multiple methods of capture would have increased the range of taxa sampled.

Mollusca

A total of 73 mollusc species were identified from the dredge samples. These comprised 3 cephalopods, 33 gastropods (including 4 opisthobranchs) and 37 bivalves. The greatest diversity of bivalves was recorded at the Gourdon Bay location (30 species), while the greatest diversity of gastropods was recorded at the Quondong to Coulomb Point location (18 species including 3 opisthobranchs).

The bivalves were represented by 16 families and 26 genera. The venus clams (Veneridae) were the most diverse group with 6 species from 5 genera identified. Many of the bivalves collected in the dredge samples are common free-living species of the soft-bottom habitats/communities of tropical northern Australia. These included the arcid species, *Trisidos senitorta*, all of the glycymerid species, post-juvenile spondylid species *Spondylus victoriae*, the pectinid species *Anuachlamys flabellatus* and species of the genus *Lima*, and all of the cardiid, semelid, mactrid, crassatellid and venerid species.

Those bivalves that were not free-living include byssate species; the arcid species of the genus *Barbatia*, the pteriid species of the genera *Pteria* and *Pinctada*, the mytilid species of the genera *Modiolus* and *Lithophaga*, the pectinid species *Minachlamys fovebris*, the pinnid species of the genus *Pinna*, and the hiatellid species of the genus *Hiatella*. The species of the genus *Pteria* commonly attach to up-standing biota such as gorgonians and seagrasses. Species of the genus *Lithophaga* burrow into dead and living corals and occasionally into soft rocks, while those of the genus *Hiatella* shelter within rock crevices or burrow into sponges, soft rock or even molluscan shells. Some non-byssate forms in this collection include the cemented species of the genus *Chama*, and the spondylid *Spondylus violascens*.

Three cephalopod species were also recorded: two from the Octopoda group, which could not be identified to species level, and one Sepiidae species. The Gastropoda in this collection consisted of 4 opisthobranchs and 30 Orthogastropoda. This latter group comprised 28 genera from 14 families with the most diverse genera being the Muricidae (7 species) and the Trochidae (5 species).

The geographic ranges of most of the mollusc species recorded in this survey are known to extend from the Central Indo-West Pacific region, along the northern coasts of Australia and southwards to the Pilbara Region of Western Australia. However, one species previously not recorded in the Kimberley region was recorded in this survey. *Acrosterigma wilsoni* was previously only known from the Muiron Islands and Ningaloo to Dampier Archipelago, WA.

The diversity of the molluscan fauna in the Kimberley area is known to be very high. Previous studies collected 292 and 232 species in western Kimberley and southern Kimberley respectively (Wells & Bryce 1995; Bryce 1997). However, there have been few detailed sampling surveys of the molluscan fauna along the mainland coasts of the Kimberley region, particularly along the western side of the Dampier Peninsula and adjacent coasts. The nearby Dampier Archipelago has also been found to be very diverse in molluscan species; a total of 695 species were recorded from intertidal and subtidal hand collection surveys in 1998–2002 (Jones 2004). More recently Bryce and Whisson (2009) found 339 species of molluscs in surveys of atolls offshore from the Kimberley at Scott and Seringapatam Reefs.

The relatively low diversity of the molluscan species taken during this survey (73 species), and the relatively high degree of variation in the species between the survey sites can be attributed to the low sampling frequency, the small size and cryptic nature of most molluscan species which are not adequately sampled by the dredging methodology used and to the limitation in data of not including dead-taken molluscan specimens. Those species that are typical of this area but are not represented in the survey samples are of small size and/or are inhabitants of specific habitats. Their absence is probably due to constraints associated with the limited number of samples at each site, meaning few habitat types were adequately covered and the type of dredging gear employed – such as large mesh size.

Echinodermata

There were 71 species of echinoderms. These included 15 crinoids (feather stars), 12 asteroids (sea stars), 18 ophiuroids (brittle stars), 14 echinoids (urchins) and 12 holothuroids (sea cucumbers). The greatest diversity of crinoids, asteroids, ophiuroids and echinoids were all recorded at the Gourdon Bay location. The greatest diversity of holothurians was recorded at the site nearest Beagle Bay (5515).

The crinoid species represented in the dredge samples were generally typical of the crinoid communities seen in the northern WA region. There were three families represented by eight genera and fourteen species. Nine of these species are from the family Comasteridae, including two from the genus *Comatula* which is generally the dominant crinoid genus in shallow waters of central and northern Western Australia. This study did not further extend any of the species distribution ranges, nor were any new species reported. The collection is much less diverse (three families and eight genera) than samples from other regions that have been studied. However little is known of the Kimberley region specifically. This lower diversity may be due to the sampling of predominantly shallow waters or from the sampling methods employed. For example, the collection appeared to be restricted to larger specimens with none of the typically smaller groups, such as the Antedonidae or the Colobometridae, recorded in the dredge samples. In addition, no species of the Calometridae family were recorded; where the reef-dwelling *Neometra* species within this family have been present in previous tropical surveys from Western Australia.

Small species of *Ophiothrix* ophiuroids were abundant in this collection, with most being *O. ciliaris*. This species shows a high level of variability and is superficially similar to *O. exigua* which was also recorded in the dredge samples. Two specimens cut across the characters that separate the species and have been identified as *O. ciliaris/exigua*. Another very small ophiuroid of the *Ophiothrix* genus was unable to be identified. Many of the ophiotrichid species are associated with sponges while *Ophiomaza cacaotica*, another species identified from our dredge samples, is commensal on large crinoids.

One species of echinoid could not be identified to any currently described species. This was a small species from the genus *Gymnechinus*. Additionally, one species of holothurian of the genus *Phyllophorus* could not be identified to species level using the currently available literature and may represent a new species. Irregular echinoids, dominated by *B. desorii* made up the highest biomass of any mobile invertebrates in this study, had biomasses comparable to habitat defining taxa such as corals and sponges and (Table 4) are likely to be of significant ecological importance in soft sediment habitats in the Kimberley region (Keesing & Irvine, in press).

All of the asteroid species in this collection have been previously recorded in north-western Australia. While this is also the case for most of the crinoids, ophiuroids, echinoids and holothurians, one species recorded here from each group have not been previously described in the current literature.

While this collection recorded 71 species, other studies in the area have recorded many more. In comparison, 286 species of echinoderms were recorded in the Dampier Archipelago (Jones 2004) with 170 of these species collected from 100 sites using rake box dredge methods, 90 other species were collected during SCUBA diving transects and the remaining 26 species were already present in the WA Museum collection. In another study, 127 species were recorded on the North-West Shelf by a broad scale trawl survey between Barrow Island and Port Hedland (20–200m) in the early 1980s (WA Museum, unpublished). In a study by the WA Museum to collate echinoderm records (excluding holothurians) for north Western Australia, 338 species were recorded on the shelf and inshore islands north of North West Cape (Marsh & Marshall 1983). Such comparative studies show this collection underestimates the echinoderm community expected.

It is notable that this collection does not contain any species of the asteroid *Luidia*, specifically the large *L. maculata* which is a known predator of heart urchins which were found to be very abundant in some areas within the four locations sampled. Overall this collection can be regarded as a subset of those of the Dampier Archipelago and North-West Shelf. Differences may be due to the sampling methods and intensity of sampling.

Summary

This study has made a significant contribution to the knowledge of a range of plant and invertebrate taxa from north-western Australia with 415 species recorded and was the first survey of subtidal habitats in the Dampier Peninsula region. Despite the limited nature of the sampling in terms of sites and area and only one method of collection (epibenthic sled), a significant number of new species, range extensions and new records for Western Australia and Australia were recorded. For some taxa (e.g. hydrozoa, alcyonaria and ascidia) these are the first published records of species occurrences from the Kimberley region of Western Australia.

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Fish-habitat associations in the region offshore from James Price Point – a rapid assessment using Baited Remote Underwater Video Stations (BRUVS)

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Abstract

A “snapshot” of the fish-habitat associations in the vicinity of James Price Point was obtained during a single expedition in October 2009, when Baited Remote Underwater Video Stations (BRUVS) were deployed in coastal waters to survey the demersal and semi-demersal ichthyofauna. A total of 7108 individuals from 116 species of fishes, sharks, rays and sea snakes were recorded from 154 sites. Bony fishes were represented by 8 orders, and cartilaginous fishes were well represented by the Carcharhiniformes, Rajiformes and Orectolobiformes. There were 2 species of hydrophiid sea snakes. Multivariate analysis showed that species responded to the amount of epibenthic cover in the study area and that there was an interaction between depth and sediment composition, as well as depth and epibenthic cover, in defining four fish assemblages to the north and south of James Price Point. Diversity appeared to increase with depth amongst these assemblages. The sandy seabed offshore from James Price Point was inhabited by a “deep sandy” fish assemblage, which intruded inshore across the study area, and was characterised by the presence of ponyfish (*Leiognathus*), threadfin bream (*Nemipterus*) and queenfish (*Scomberoides*). On either side were shallow, northern and deeper, southern, assemblages inhabiting “gardens” of macroalgae, filter-feeders and some seagrass beds. These epibenthic habitats at the northern and southern ends of the survey area were clearly important to many species, but in general there appeared to be little association of particular vertebrate species or biotic habitat types with the James Price Point area itself. The study area was notable for the diversity and abundance of the fauna, given the shallow depth, lack of rugose seafloor topography and lack of sub-tidal coral reefs in the area sampled. Coarse comparison with the fauna at similar distance to shore in similar latitudes in the Great Barrier Reef Marine Park, the Burrup Peninsula and the Kimberley indicated that the study area had more small pelagic planktivores and more large semi-demersal predators. There was also an absence of some species normally associated with muddy seafloors and fringing coral reefs that are common on BRUVS set elsewhere in regions with less extreme tidal ranges.

Keywords: fish-habitat, James Price Point, Kimberley, BRUVS

Introduction

The inshore margins of tropical shelves are comprised of mosaics of soft-bottom communities interspersed with shoals, patches and isolates of ‘hard ground’ supporting large epibenthic plants and filter-feeders. Knowledge of fish-habitat associations in these mosaics is generally very poor in the Kimberley coast, with few inshore surveys (Hutchins 2001, Travers *et al.* 2006, 2010). This paucity contrasts starkly with paradigms about the importance to fishes of sponges, and other megabenthos, derived from trawl grounds of the north-west shelf (Sainsbury *et al.* 1997). In comparison to shallow reefal habitats studied elsewhere, the Kimberley coast poses special challenges due to its remote location, extreme tidal movements, episodic storms, and heavy load of suspended materials in the water column. The abundance of crocodiles, sharks and toxic stinging jellyfish also discourage direct observation by SCUBA divers. Despite these conditions, underwater visual

surveys (UVC) using timed “zig-zag” swims have been used to describe the ichthyofauna at coastal sites between Broome and Cape Leveque at depths mainly shallower than 20 metres by Hutchins (2001). Demersal trawl gear and baited fish traps have also been used in deeper waters in the Canning bioregion to describe ichthyofaunal groupings on “soft” and “hard” seabeds (Travers *et al.* 2006, 2010). These studies have been aimed mainly at detecting spatial boundaries and placing the ichthyofauna in a bioregional context (*e.g.* Fox & Beckley 2005), and have not incorporated fine-scale measurements of the nature of sediments and epibenthos at the sampling sites.

Environmental impact studies for the proposed industrial development of the James Price Point region require biologically-informed spatial models of species occurrence at much smaller scales of association of fish species with features of the local seabed. The challenge in providing useful information on the local ichthyofauna is therefore two-fold. Firstly, standardised approaches to sample all depths and seafloor topographies of the region must be applied. Such techniques should simultaneously

measure fish and habitat covariates and have the least selectivity possible, given the fact that a narrow focus in baseline studies and monitoring programs (on a few economically important predators for example) has high risk of failing to detect fundamental changes in biodiversity. Secondly, robust models must be developed that explain and predict the distribution of species and assemblages along critical environmental gradients.

In this rapid assessment we used a harmless baited video technique that offered the benefits of detecting fishes of any size for visual census on seabed topographies of any rugosity and depth. This technique records mobile fish passively traversing the field of view or actively following the bait plume, and allows direct observation of the fine-scale substratum and epibenthos inhabited by the fish in the field of view. Baited videophotography has proven especially successful in studies of abyssal scavengers, juvenile lutjanids, the fate of bycatch discards, and the densities of carnivorous fish inside and outside marine protected areas (see Cappo *et al.* 2007a for review). It has been chosen elsewhere in tropical northern Australia to overcome the limits to UVC imposed by turbidity inshore (Gomelyuk 2009) for standardised surveys of fish biodiversity (Cappo *et al.* 2007b; Watson *et al.* 2008).

In this rapid assessment we applied a fleet of eight replicate BRUVS (Baited Remote Underwater Video Stations) simultaneously to describe the spatial patterns of species richness and assemblage structure of the ichthyofauna in the vicinity of James Price Point. Our main aim in this paper was to analyse the responses of species occurrence at each sampling site to the depth, position and epibenthic cover of key groups of marine plants and filter feeders. Our secondary aims were to analyse the effect of underwater visibility on the number of species recorded by the baited video technique, and to compare the local indices of diversity and abundance with the same measurements recorded from similar habitats by BRUVS in the Great Barrier Reef lagoon.

Methods

Survey design

The survey region was a ~30km x 14km (~420km²) stretch of sub-tidal coastal shelf extending from 17.7° – 17.3° South, from the 5m Lowest Astronomical Tide (LAT) isobath, seaward to 122.03° East. The study area was generally less than 20 metres (LAT) in depth (Figure 1). This area encompassed spatial gradients and contained habitat gradients and strata identified in previous studies (Fry *et al.* 2008). The survey employed a spatially interspersed design that aimed to sample habitats in proportion to their availability, thus enabling differences amongst habitats to be estimated robustly. The specified survey area was divided into 160 equal sized units and excluded the local pearl farm leases. Within each unit random coordinates were determined for BRUVS placement, conditional on the sampling point being >450m from the nearest neighbouring BRUVS deployment. Most species were unlikely to move this distance in the short period between consecutive deployments (see Cappo *et al.* 2004). BRUVS were deployed in latitudinal blocks of 32, and each block was

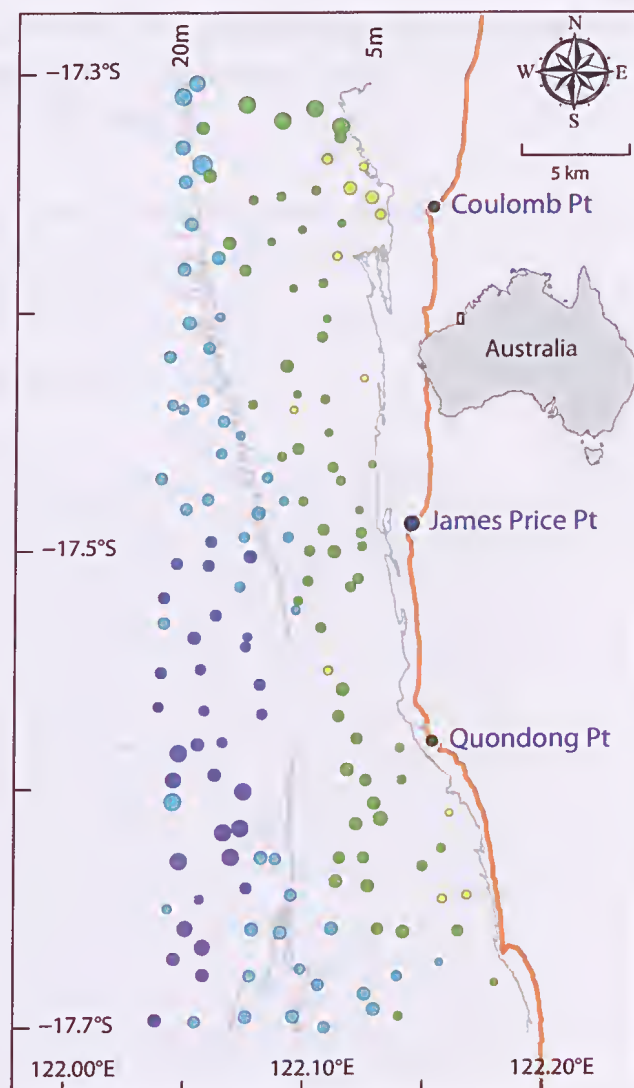


Figure 1. The location of 154 successful BRUVS deployments. The 5m and 20m depth contours at lowest astronomical tide (LAT) are shown offshore from the coast. The size of site symbols has been scaled by estimates of underwater visibility. The colour ramp from yellow to blue represents increments of 6 metres depth recorded at the time of BRUVS drops. James Price Point, Coulomb Point and Quondong Point are shown on the coastline.

sampled in a single day. Fleets of 8 BRUVS were deployed at a time, with fleets interspersed over the latitudinal and longitudinal gradient of the block to avoid temporal confounding with tidal movement. All sampling was carried out around the neap tides of 11–15 October 2009.

BRUVS deployments and tape interrogation

The BRUVS consisted of a galvanised steel frame onto which a camera housing, bait arm, ballast weights, ropes and floats were attached (see Fig. 2). A Sony MiniDV tape "Handicam" was used to film through an acrylic port within a PVC underwater housing, pressure-rated to depths of 100m. A flexible bait arm held a plastic mesh bait bag containing 1 kg of minced pilchards (*Sardinops sagax neopilchardus*) at a distance of approximately 1.5 m in front of the camera lens. The bait bag lay on the seabed

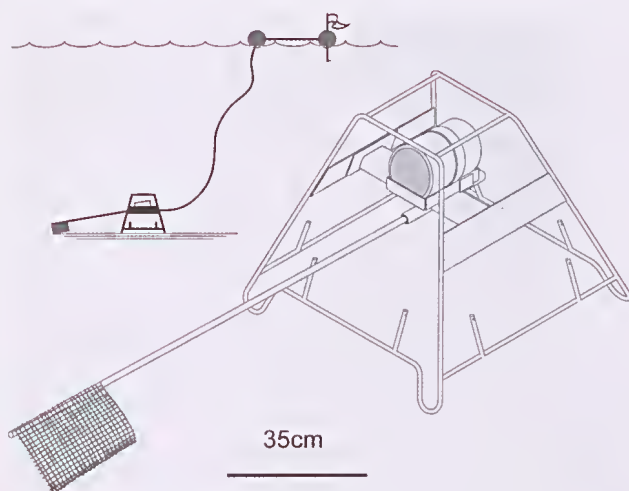


Figure 2. The AIMS BRUVS assembly.

in the field of view, with the camera tilted downwards at an angle of 10 degrees.

The AIMS BRUVS2.5.mdb[®] database provided an interface with a video playback device to capture time codes and still images and to store and record data. The interface allowed for standardised identification and quantification of habitat types and fish numbers in the immediate field of view, the timing of events and comparison of video frames with a library of reference images. The relative abundance of vertebrates in the video footage was estimated by *MaxN*, defined by the maximum number of each species visible at any single point on the tape. The use of this conservative metric was reviewed by Cappo *et al.* (2003).

The percentage cover of abiotic substratum types and biotic habitat types in the field of view was estimated from still images captured as soon as the BRUVS settled on the seafloor. The categories in terms of substratum type were sand, gravel, rubble, calcareous reef, indeterminate, boulder, and bedrock. The seven categories scored for epibenthic cover were none, seagrass, macroalgae, sea whips, soft corals, sponges, and gorgonian sea fans with each component estimated to the nearest 10 percent. Underwater visibility was estimated subjectively to the nearest metre when viewing the BRUVS tapes.

Statistical analyses

The partial effects of depth, total epibenthic cover, longitude, latitude and underwater visibility on species richness were investigated using aggregated boosted regression trees (abt; see De'ath 2007, Elith *et al.* 2008). Boosted regression trees are a statistical learning method that optimises both the explanatory and predictive power of regression and classification analyses. Non-linear interactions between predictors were quantified and visualised using partial effects plots. Generalized additive models (gam) based on spatial position alone were used to develop a smoothing function for species richness (see Venables & Ripley 2002). Contour plots of the model fits were overlain with symbols scaled to the observed levels of total epibenthic cover at each BRUVS site. Boxplots of the medians in the number of

species, genera, families and individuals were compared between the James Price Point dataset and a subset of the BRUVS data for the Great Barrier Reef (GBR) lagoon (see Cappo *et al.* 2007b). This subset of 142 samples in the GBR lagoon was selected for similarity to the James Price Point study area in terms of distance from shore (< 15.45 kilometres) and depth (< 24.4 metres).

No species occurred at all sites, so use of presence-absence data alone was used to amplify the contribution to models of common species with low abundance. Multivariate responses at each BRUVS site, in the form of the occurrence of a subset of the 59 most prevalent species (occurring at more than 4 sites), to a relatively large number of environmental covariates were defined with a redundancy analysis (rda; Borcard *et al.* 2011) and multivariate regression trees (MRT; see De'ath 2002). The explanatory covariates included the percentage cover of sediment types and categories of epibenthos described above. Centring of the species by site response matrix was done for the redundancy analysis by subtracting the column means of each species from their corresponding columns, and scaling was done by dividing the (centred) columns of each species by their root-mean-square.

Indicator values (DLI; Dufrêne & Legendre 1997) were calculated for each species for each assemblage (nodes and terminal leaves) identified in the MRT. For a given species and a given group of BRUVS sites, the DLI was defined as the product of the mean species prevalence occurring in the group divided by the sum of the mean prevalence in all other groups (specificity), times the proportion of sites within the group where the species occurs (fidelity), multiplied by 100. The DLI has a maximum value of 100 if the species occurs at all sites in the group and nowhere else. Each species can be associated with the tree node (assemblage) where its maximum DLI value occurred. Species with high DLI can be used as characteristic representatives of each assemblage, and the spatial extent of the group indicated the region near James Price Point where the assemblage was predominantly found. Species accumulation curves (SAC) were used to record the rate at which new species (*y*) were added with continued sampling effort (*x*) in each assemblage identified by the MRT (see Gotelli & Colwell 2001; Thompson *et al.* 2003). The analyses used the open-source R statistical package (R Development Core Team 2006) with the libraries of De'ath (2007). The use of common and scientific names follows those reported in Allen & Swainston (1988).

Results

Habitat types and their distribution

There were three major regions of cross-shelf zonation in the study area proximal to each of the coastal points (Figure 3). The cross-shelf zone off Coulomb Point in the north was comprised of mixed patches of bare ground and beds of marine plants and filter-feeders, and some BRUVS landed in seagrass beds inshore. There was a broad band of bare sand extending offshore from James Price Point. Off Quondong Point there was a sandy coastal bench inshore of a ridge of high diversity and abundance of epibenthos parallel to the 20m depth

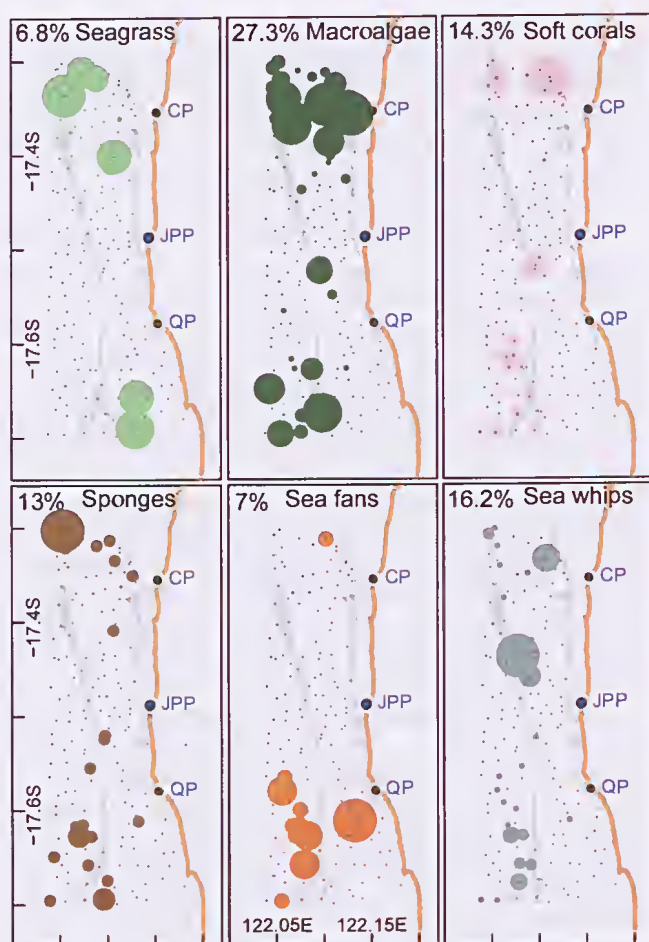


Figure 3. The percentage cover of epibenthos at all BRUVS sites by category, showing the percentage of sites where each category was recorded. Bubbles are scaled to the maximum percentage cover recorded within each category.

contour. Marine plants and filter-feeding sponges, gorgonian fans, and soft corals had increased levels of epibenthic cover in the northern and southern parts of the study area. The bare sandy habitats were physically structured into sand ripples in shallow waters, and low dunes in deeper waters.

Sea whips were found mainly in the south in a line parallel to the 20m depth contour. Along this line there was clear evidence of a low ridge of exposed bedrock, or a long-shelf band of coarser sediment, that supported the attachment of holdfasts by filter-feeders. A similar linear pattern in the south was seen for the sponges and soft corals. Seagrasses were not a common feature of the epibenthos in the BRUVS sets, and were most abundant in the shallows of the north and south between the 5m and 20m depth contours. Macroalgae were more widespread, on 27.3% of BRUVS sets, but were most abundant in the north and south in co-occurrence with filter-feeders.

The entire study area was shallow, with all samples <25 metres, so benthic irradiance was sufficient to allow macroalgae and filter-feeders to occur together in dense patches on some BRUVS sites where bedrock or consolidated gravel was present. No hard corals were seen on BRUVS sets, and the major "reefal" habitats were comprised of mixed beds of macroalgae and filter-feeders

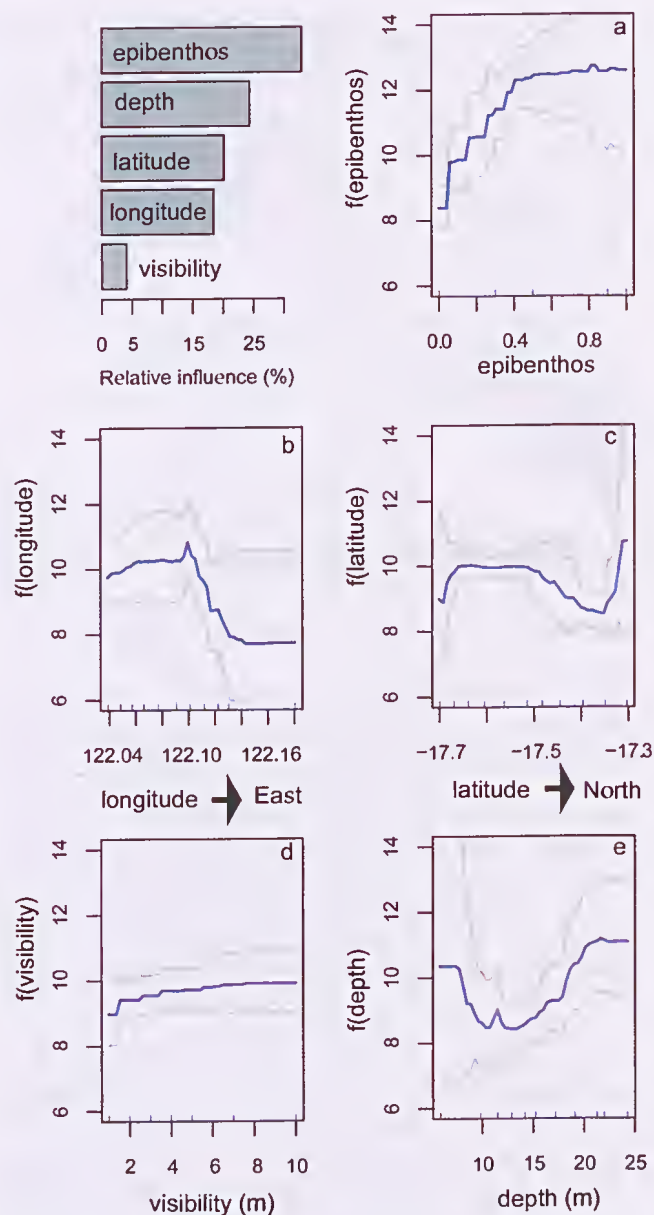


Figure 4. Relative variable importance plot and partial dependency plots for boosted tree analyses of the species richness data. The importance plot shows their relative contributions (%) to predicting species richness, and the five partial plots show the dependencies of richness on epibenthic cover (a), longitude (b), latitude (c), underwater visibility (d) and water depth (e). The gray lines show 95% confidence intervals. The distribution of values of the predictor variables is indicated by tick marks above the x-axes, showing deciles. Dotted vertical lines indicate the mean value for each predictor, and horizontal lines show the mean species richness in the entire dataset (10.15).

on harder seafloors of low topographic relief. Larger rocks and boulders were not seen, and the bare sandy habitats were arranged in ripples, indicating that the sub-tidal substratum was being heavily scoured and redistributed by both Indian Ocean swells and the 8 metre tidal range. Habitats supporting stony corals, or dominated by them, have been reported to occur on the inshore margin of the study area (Fry *et al.* 2008), but they were too shallow or turbid to be accessed by the BRUVS survey vessel.

The fauna

A total of 7108 individuals from 116 species of fishes, sharks, rays and seasnakes were recorded from the 154 sites. Bony fishes were represented by 8 orders, and dominated by perch-like fishes (Perciformes 79 species), whilst cartilaginous fishes were well represented by 19 species from three orders. There were also two species of sea snakes from the family Hydrophiidae (Appendix 1). Only three species were considered to be endemic to Western Australia – the frostback cod *Epinephelus bilobatus*, the western butterfish *Pentapodus villa* and the blue-spotted tuskfish *Choerodon cauteroma* (Hutchins 2001). The top 20 species are shown in Table 1. A wide range of functional groups was present in this fauna, although herbivores were rare and the predominant groups were carnivores that feed either on the seafloor or in the water column, and mobile predators of nekton and zooplankton.

Effects of visibility, position and epibenthic cover on species richness

The partial effects plots in Figure 4 show that there was a marginal, non-significant effect of underwater visibility on the performance of BRUVS. On average there were 10.15 species identified in each sample, but over a 9 metre range in visibility there was a diminution of only 1 species less than this average. The response was non-linear, with the drop in performance only at the lowest visibility (~1 metre). The total amount of epibenthic cover was the most important influence on species richness in the model, accounting for 34% of the variation explained. Depth (24%), latitude (20%) and longitude (18%) were also important, but underwater visibility accounted for only 6% of the variation explained (Fig. 4).

All sites where epibenthic cover was above average (~20%) had species richness above the mean, but this flattened off at 2 extra species for sites with epibenthic cover >40%. The partial effects of longitude were sigmoidal, with species richness declining towards shore in the eastern half of the study area. Richness initially declined in the northern half of the study area, but then rose above the average at the northern boundary. Richness fell to a minimum about 10–14 metres depth, but rose to above average levels in water deeper than 20 metres.

Contour plots showed that the model of species richness predicted by position (latitude and longitude) alone did not strictly follow the total abundance of epibenthic structure on the seabed (Fig. 5). However, there were two coarse groups of sites with both high richness and more habitat complexity to the north and south of James Price Point. A long-shore belt of lower diversity (<8 species) extended from the south up to James Price Point and then spread offshore into a broad zone with 8–10 species. The zones of highest diversity in the south and north had species richness >14, which appeared to be increasing above 18 along the northern boundary of the study area (Fig. 5).

Comparison with the GBR lagoon

The significant lack of overlap in the 95% confidence intervals for the medians (notches) in Figure 6 show that the ichthyofauna in the James Price Point study area had much higher diversity and abundance compared to BRUVS samples from equivalent positions in the GBR lagoon. The medians differed significantly by a factor of 2 for richness, 1.8 for the number of genera, 1.75 for the number of families and 2.8 for fish abundance (Fig. 6). The median number of orders (1) was the same for each area. The ratio of mean values for fish abundance (2.01) and richness of species (1.74), genera (1.76), families (1.58) and orders (1.15) also indicated strong differences.

Table 1

The top 20 species sighted on BRUVS, in descending order of occurrence (presence/absence) on 154 BRUVS sets in the study area off James Price Point. The percentage contribution of each species to the overall data set ($\Sigma \text{MaxN} = 7108$ individuals) is shown in terms of numbers counted and prevalence on BRUVS sets (%occ). The relative rank* in the stereo-BRUVS data from Burrup Peninsula (Watson *et al.* 2008) is also shown.

Family	Common Name	Species	% ΣMaxN	%occ	rank*
Scombridae	School mackerel	<i>Scomberomorus queenslandicus</i>	4.6	89.6	1
Nemipteridae	False whiptail	<i>Pentapodus porosus</i>	15.2	77.3	3
Carangidae	Smooth-tailed trevally	<i>Selaroides leptolepis</i>	18.9	70.8	–
Carangidae	Yellowtail scad	<i>Atlule mate</i>	15.6	55.8	–
Carangidae	Bumpnose trevally	<i>Carangoides hedlandensis</i>	1.3	34.4	–
Lethrinidae	Blue-spotted emperor	<i>Lethrinus punctulatus</i>	7.3	33.1	10
Carangidae	Golden trevally	<i>Gnathanodon speciosus</i>	2.4	29.2	–
Leiognathidae	Smithurst's ponyfish	<i>Leiognathus longispinis</i>	4.6	26	–
Lutjanidae	Stripey seaperch	<i>Lutjanus carponotatus</i>	1.3	26	12
Pinguipedidae	Red-banded grubfish	<i>Parapercis multiplacata</i>	1	24.7	–
Carangidae	Goldspot trevally	<i>Carangoides fulvoguttatus</i>	0.8	22.7	9
Nemipteridae	Rosy threadfin bream	<i>Nemipterus furcosus</i>	2.4	21.4	–
Pomacanthidae	Scribbled angelfish	<i>Chaetodontoplus duboulayi</i>	0.7	21.4	8
Carcharhinidae	Aust. blacktip shark	<i>Carcharhinus tilstoni</i>	0.5	20.8	–
Echeneidae	Suckerfish	<i>Echeneis naucrates</i>	0.6	20.1	9
Serranidae	Frostback cod	<i>Epinephelus bilobatus</i>	0.6	19.5	11
Carangidae	Queenfish	<i>Scomberoides commersonnianus</i>	0.4	18.8	–
Nemipteridae	Western butterfish	<i>Pentapodus villa</i>	1	18.2	–
Labridae	Purple tuskfish	<i>Choerodon cephalotes</i>	0.6	18.2	–
Labridae	Bluespotted tuskfish	<i>Choerodon cauteroma</i>	0.5	17.5	4

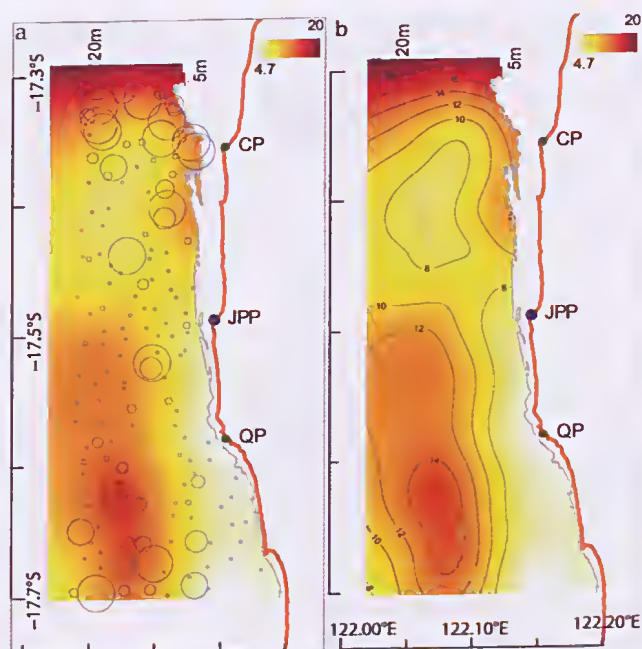


Figure 5. Smoothed spline fits (gam) of the total number of species recorded at BRUVS sites. Site symbols on panel (a) are scaled to the amount of epibenthos of all categories (summed percentage cover) seen in the field of view. Diversity contours (b) and the colour ramp show that richness predicted by position alone did not strictly follow the abundance of epibenthic structure on the seabed, although there were two groups of sites with both high richness and more habitat complexity to the north and south of James Price Point (JPP). Coulomb Point (CP) and Quondong Point (QP) are also shown on the coastline.

Associations between fishes and habitats

All environmental and spatial variables were significant in a redundancy analysis using constrained eigenvalues, and the model explained about 19% of the total variation in the species occurrence at each BRUVS site (Fig. 7). The first axis accounted for 47.6% of the total variation (19%) explained by all the axes in the model, indicating that BRUVS sites were separated first by the amount, or absence, of epibenthos, and then (on the second axis) by depth and latitude. Deeper sandy sites were separated from shallower sandy sites along this axis, as were the northern "garden" seafloors where macroalgae and seagrass were more abundant in the shallower water. Sponges, gorgonian fans and sea whips were more abundant in the southern, deeper parts of the study area.

The site symbols in the biplots of Figure (7) are coloured by their membership of the four vertebrate assemblages distinguished in the MRT analysis described below. The linear combination scores for sites on the biplots showed that bare, sandy habitats were located on gradients of both depth and latitude. The deeper "southern gardens" encompassed more filter feeding epibenthos, and the "northern gardens" included more habitats dominated by macroalgae and seagrass. The biplots showed that the ichthyofauna was broadly organized into three groups on the first two dimensions: (1) ubiquitous, generalist species that were either independent of, or in some cases negatively associated with, biotic habitat; (2) species that were associated with

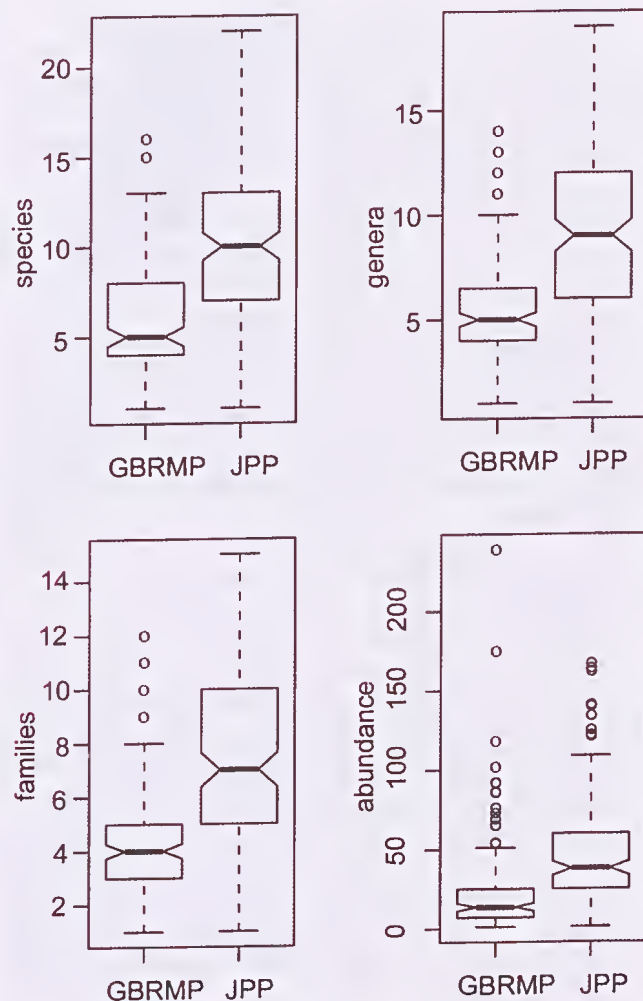


Figure 6. Comparisons of the median richness of species (a), genera (b), families (c), and fish abundance (ΣMaxN) (d) recorded by $n=142$ BRUVS in the Great Barrier Reef Marine Park (GBRMP) and $n=154$ BRUVS in the current study (JPP). The boxplots show the median and 95% Confidence Intervals. The notches represent $1.5 \times (\text{interquartile range of } \Sigma\text{MaxN}/\text{SQRT}(n))$. If the notches do not overlap this is strong evidence that the two medians differ, independent of any assumptions about normality of data distributions or equivalence of variances (Chambers *et al.* 1983).

vegetated habitats, and (3) species that were associated with filter-feeding epibenthos. There was no evidence of strict associations between particular species and particular types of epibenthos. For example, the "northern gardens" sites were inhabited by more purple tuskfish *Choerodon cephalotes* and blue-spotted emperor *Lethrinus punctulatus*, but they were not restricted to these sites.

Assemblage-level patterns in fish-habitat associations

At the third and final split in the multivariate regression tree of the same responses and explanatory variables described above, the MRT had explained 16.3% of the species variation (Fig. 8). The first split in the tree, based on low levels of bare sediment, explained 9.5% of the species variation, whereas the next split (depth < 18m) explained 4.5% of variation, and the final split (latitude < -17.40°S) accounted for 2.3%. An examination of the

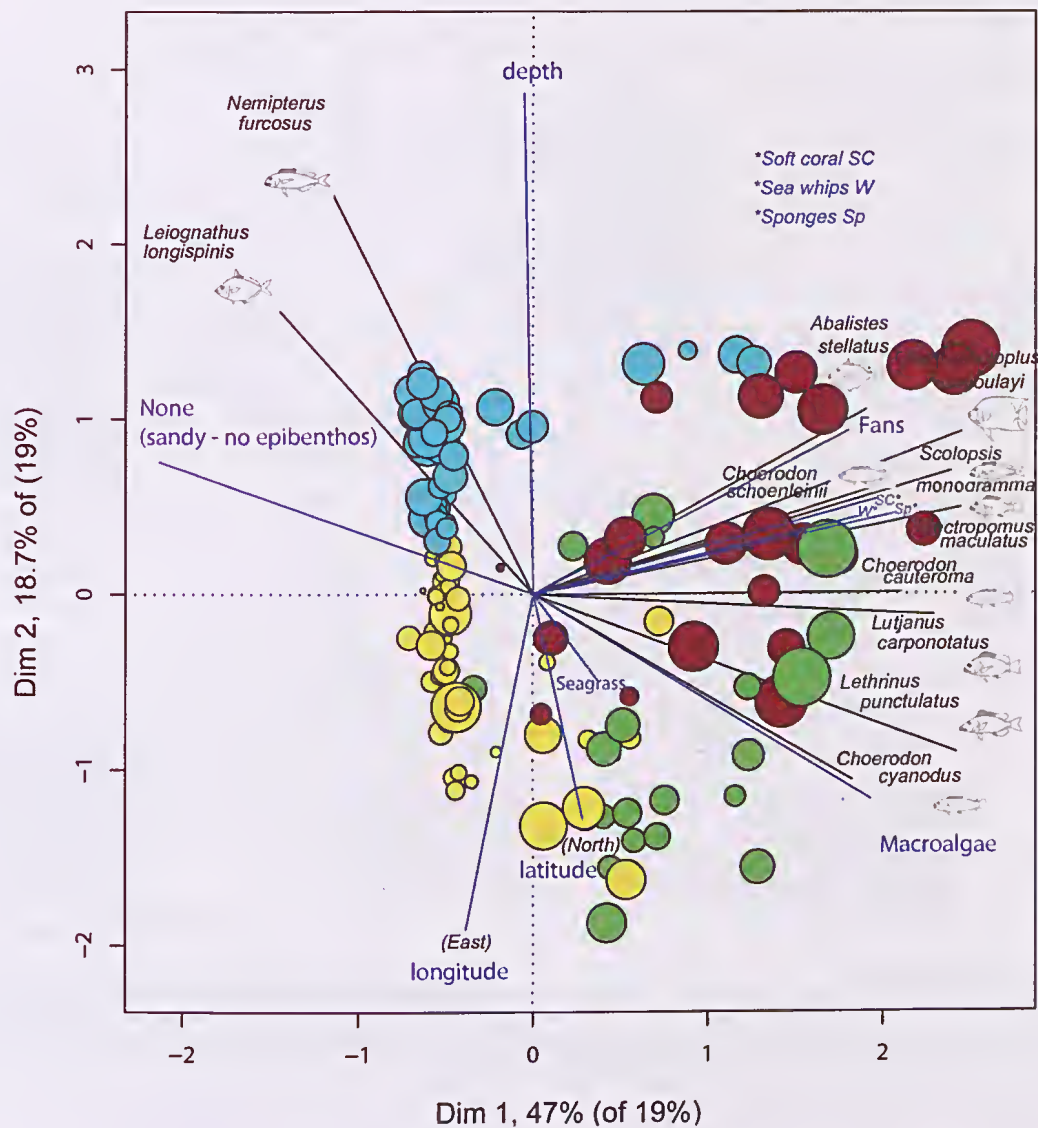


Figure 7. Biplot scaled by species scores from a redundancy analysis of the occurrence (presence/absence) of the 59 most prevalent species constrained by position, depth and percentage cover of the seafloor by epifauna and epifauna. Only the longest 20% of species vectors are shown. The fitted scores (linear combinations of constraining variables) for each BRUVS site are coloured by their membership of four fish assemblages identified by multivariate regression trees (see Figure 8). The assemblages are “deep sandy” (light blue), “shallow sandy” (yellow), “northern gardens” (light green) and “southern gardens” (brown). The symbols are scaled by the species richness (divided by 4) at each site.

surrogates at the first split showed that “none” improved the model by 9.5%, in competition with 7.1% for “macroalgae” and 5.0 – 5.9% for “sea whips”, “sponges”, and “soft coral”. This occurred because the categories of seafloor cover were complementary, so that (100-“none”) represents the amount (percentage cover) of epibenthos of all categories in the field of view.

At the second split, the nearest surrogate for depth < 18m (improving the model by 7.5%) was longitude < 122.084° E, which improved the model by 5.9%. The study area lay in a north-south alignment and depth varied across the shelf with contours parallel to the coast. Thus it was not surprising that longitude was a close surrogate for depth. At the final split, based on latitude < -17.40 °S, the nearest surrogate was depth < 15.45 metres. The spread of the depth contours offshore from the coastline to the north of James Price Point show

the shallower waters there (see Fig. 1). In fact, all the deepest BRUVS sites were located to the south of James Price Point (about -17.49°S). The species richness and abundance of all species sighted at sites in the “shallow sandy”, “deep sandy”, shallow “northern gardens” and deeper “southern gardens” are shown in Table 2. Richness appeared to increase with depth amongst the assemblages of both “bare” and “garden” types. The location of sites within these assemblages is shown in Figure 9.

Species indicators for local assemblages

The top 10 Dufrène-Legendre Indices (species DLI) are shown for each node and terminal “leaf” of the tree in Figure 8. The tree is hierarchical, so species that were ubiquitous in the study area, such as the school mackerel *Scomberomorus queenslandicus*, were located at the tree

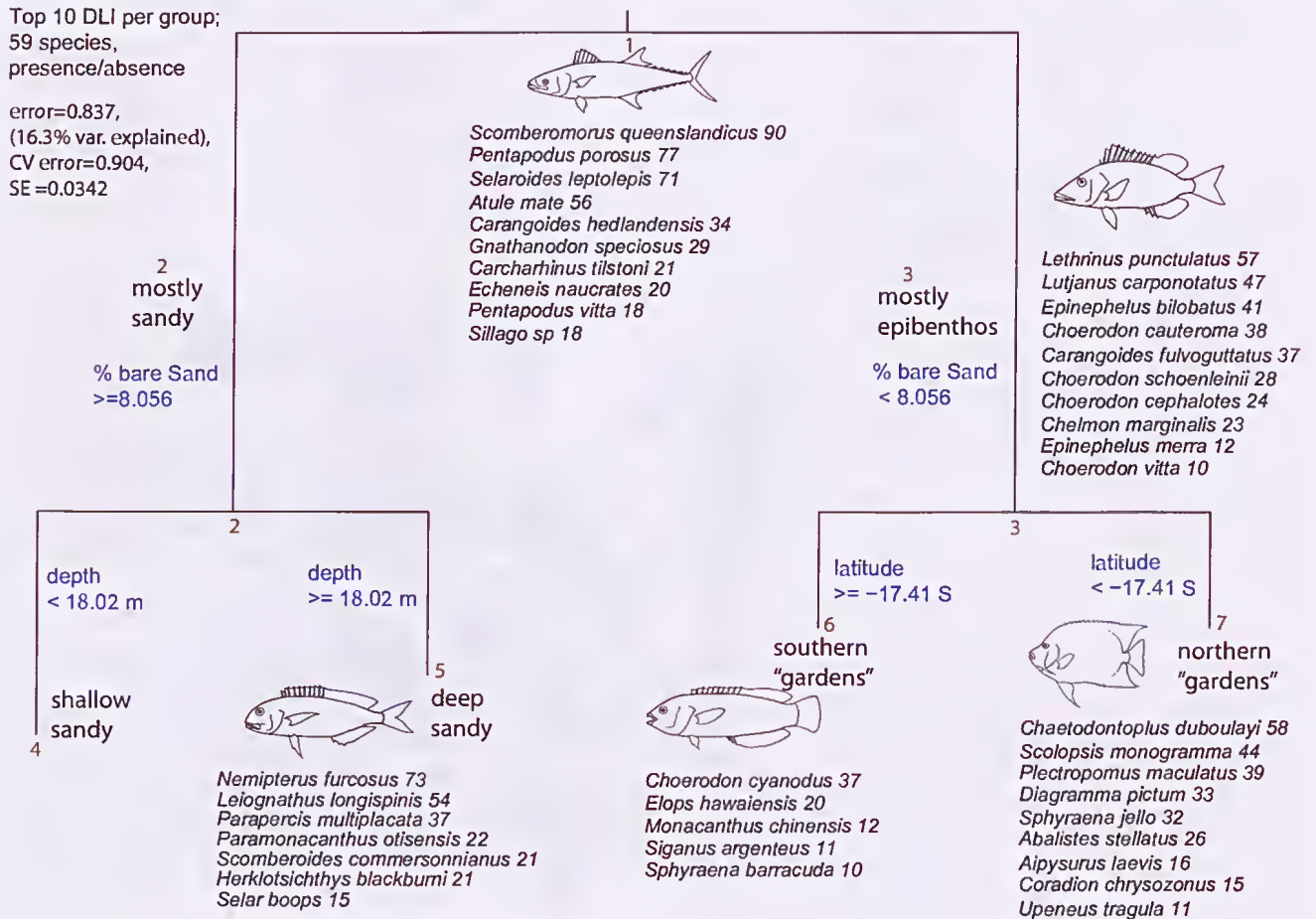


Figure 8. Multivariate regression tree (MRT) analysis of the occurrence of the 59 most prevalent species. This model explained 14% of the variation of these 59 species in response to position, depth and epibenthic "cover". Species at the stump were ubiquitous. The top 10 Dufrène-Legendre Indices (species DLI) are shown for each node. Some nodes and leaves had no DLI, because species that occurred there also occurred elsewhere in the tree with higher fidelity and specificity.

stump. A list of others known to inhabit many types of rugose habitats (e.g. *Lethrinus*, *Lutjanus*, *Choerodon*, *Epinephelus*) characterised the "epibenthos" node, on the side of the tree where the leaves were the deep southern grounds and the shallow northern beds.

On the other side of the tree the bare seafloor habitats were distinguished by indicator species only in the deeper waters. The "shallow sandy" assemblage had no DLI, because the numerous species that occurred there also occurred elsewhere with higher frequency. The

species accumulation curves in Figure 10 show that the shallow sandy assemblage was the most diverse, yet it had no DLI indicator species. This implied that many species occurred there, but they were more prevalent at other nodes and leaves of the tree. The assemblages characterised by the cover of epibenthos comprised relatively few sites (< 23 sites each) and showed no sign of reaching an asymptote – indicating that there remained much latent diversity to be sampled in those assemblages.

Table 2

Summaries of the abundance ($\Sigma MaxN$) (N) and richness (S) of all the 116 species from sites included in each assemblage identified from the distribution of 59 more prevalent species in Figure 6.

n BRUVS	assemblage	$\Sigma richness$ (S)	$\Sigma MaxN$ (N)	S range	S mean	N range	N mean
69	Shallow Sandy	77	2044	(1 – 19)	(7.1 $\pm$ 3.9)	(1 – 102)	(29.6 $\pm$ 21.8)
43	Deep Sandy	66	2855	(7 – 18)	(11.3 $\pm$ 2.7)	(21 – 167)	(66.4 $\pm$ 38.2)
20	Nthn Gardens	65	956	(8 – 22)	(12.5 $\pm$ 4.2)	(15 – 88)	(47.8 $\pm$ 19.8)
22	Sthn Gardens	66	1253	(3 – 22)	(15.2 $\pm$ 4.7)	(4 – 141)	(57 $\pm$ 36.8)

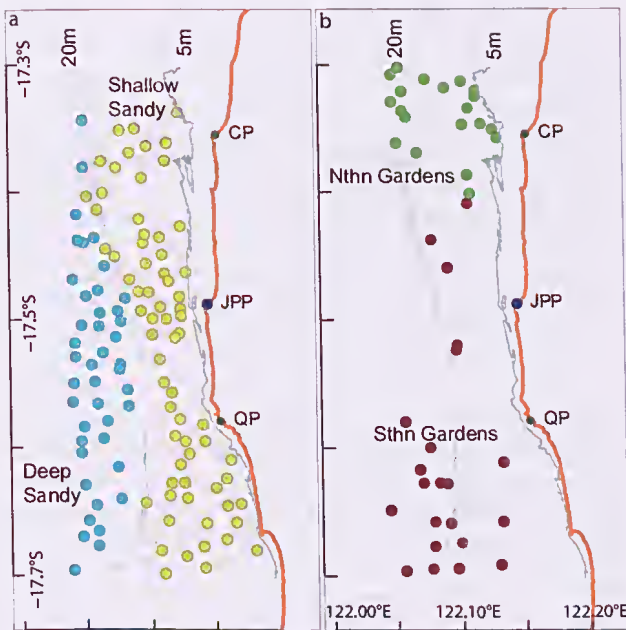


Figure 9. Location of sites in the four vertebrate assemblages distinguished by the multivariate regression tree (MRT) analysis in Figure 8. The shallow and deep “bare sandy” assemblages were separated near the 20m [LAT] depth contour, where wave action at the seabed is generally diminished. The sites where epibenthic cover (of marine plants and/or filter-feeders) was greater than 90% formed northern and southern groups.

Discussion

The results presented here show that the ichthyofauna around James Price Point was diverse and abundant, given the shallow depth, lack of rugose seafloor topography and lack of sub-tidal coral reefs in the area sampled. The diversity and abundance of large, predatory, vertebrates so close to shore in relatively shallow water was remarkable in comparison to similar seascapes from the Great Barrier Reef lagoon (Cappo *et al.* 2007b) and Burrup Peninsula (Watson *et al.* 2008). The abundance of small pelagic “baitfish” (such as clupeid sardines, yellowtail scads and smooth-tailed trevally) was accompanied by a correspondingly high occurrence and abundance of schooling, predatory carangid trevallies and scombrid mackerels known to include fish in their diets. Apex predators including large sphyraenid barracudas, and carcharhinid (whalers) and sphyrnid (hammerhead) sharks, were common.

There were three major regions of cross-shelf zonation in the study area proximal to each of the coastal points. The species richness showed two coarse groups of sites with both high richness and more habitat complexity to the north and south of James Price Point. A long-shore belt of lower richness extended from the south up to James Price Point and then spread offshore into a broad sandy zone. The zones of highest richness in the south and north had more than 14 species, increasing beyond 18 species along the northern boundary of the study area. Underwater visibility had very low influence on the number of species sighted on the BRUVS, giving us confidence that this technique will be useful in macrotidal tropical areas when sampling on neap tides. It is probable that tidal scouring removes much of the

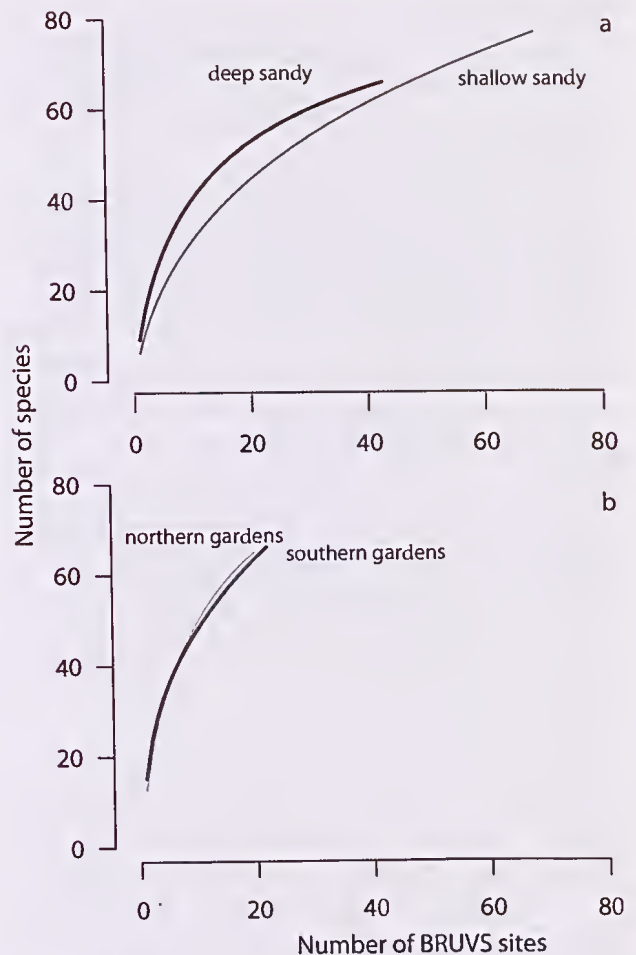


Figure 10. Species rarefaction curves for the four vertebrate assemblages distinguished by the multivariate regression tree (MRT) analysis of the presence/absence of 59 species. The shallow sandy assemblage was the most diverse, yet it had no DLI indicator species. The assemblages in epibenthic “gardens” showed no sign of reaching an asymptote – indicating that there remained much latent diversity in those assemblages. More sampling would be needed to adequately measure that latent diversity.

fine silt from the inshore sediments, so that suspended solids settle quickly when tidal movement ceases.

The most parsimonious model of assemblage structure constrained by depth, position and nature of the epibenthos separated BRUVS sites in the “shallow sandy”, “deep sandy”, shallow “northern gardens” and deeper “southern gardens”. Diversity appeared to increase with depth amongst the assemblages of both “bare” and “garden” types. This may well indicate the presence of an interaction between depth and sediment composition, or sediment grain size, in defining fish assemblages. Analysis of the Dufrene-Legendre Indices (species DLI) for each assemblage showed that epibenthos in both the north and south were characterised by the labrid tuskfishes, lethrinid emperors, lutjanid snappers and serranid cods known to inhabit rugose topography elsewhere (Travers *et al.* 2006, Cappo *et al.* 2007b). For example, painted sweetlips (*Diagramma*), coral trout (*Plectropomus*), angelfish (*Chnetodontoplus*) and

triggerfish (*Abalistes*) characterised the deeper (~20m) southern ridge of epibenthos north of Quondong Point. The "deep sandy" assemblage, which intruded inshore to James Price Point, was characterised by ponyfish (*Leiognathus*), threadfin bream (*Nemipterus*) and queenfish (*Scomberoides*).

The assemblage structure indentified here reflected the functional form and habitat preferences of the fauna, so that some demersal carnivores were associated more with epibenthos in the north and south than with bare sandy substrata, and the most prevalent species were ubiquitous throughout the study area in all the habitat types sampled. These same prevalent species (the school mackerel *Scomberomorus queenslandicus* and the false whiptail *Pentapodus porosus*) were in the top three species sighted on stereo-BRUVS deployed off the Burrup Peninsula by Watson *et al.* (2008). Like estuarine fish faunas (Magurran & Henderson 2003), the ichthyofauna comprised 'core species', which are persistent, abundant and biologically associated with particular habitats, and 'occasional species' which occur infrequently in surveys, are typically low in abundance and have different habitat requirements. Species accumulation curves for such assemblages are generally long and high (Thompson & Withers 2003) with many samples needed to obtain comprehensive species lists.

Macroalgae and filter-feeders co-occurred in beds (or banks) where the waters were shallow enough to allow photosynthesis to occur. As expected for such mixed habitats, benthic macro-carnivores (e.g. wrasses, emperors and snappers) were common. Such groups prey on infauna, epifauna, natant crustacea, and benthopelagic cephalopods. Tuskfishes of the genus *Choerodon* were also expected to occur there because they have similar broad range in diet, but they also have specialised dentition and massive jaw muscles that enable them to grasp and wrench off hard-shelled prey, such as limpets and gastropods, from hard substrata. Habitats supporting marine plants such as fleshy macroalgae and seagrasses are also known to provide nursery sites for lethrinid emperors (Wilson 1998, Nakamura *et al.* 2009) as well as the foundations of food chains based on grazers and detrital pools.

The plectorhynchid *Diagramma* recorded in the study area is also well known to inhabit megabenthos patches in the Indo-Pacific and feeds by suction and sifting of pockets of finer sediment (Cappo 2010). The whiting *Sillago* sp, ponyfish *Leiognathus loughispinis* and threadfin bream *Nemipterus furcosus* associated with bare sandy sediments are known to consume infauna and small natant crustaceans. Slow-moving balistids, monacanthids and tetraodontids were also prevalent in the study area. These three families have teeth fused into very powerful cutting plates that allow them to eat a wide variety of plant and animal food sources, such as sponges, echinoderms and heavily-armoured decapods and sedentary fish. The tetraodontiformes employ toxins, armature and behavioural defences that allow them to occupy a wide variety of niches where there is no shelter from larger predators.

Quantitative comparisons between studies within the Kimberley region using BRUVS, UVC (Hutchins 2001), traps and trawls (Travers *et al.* 2006, 2010) cannot be made because of the different selectivity of each

technique that applies a "filter" to the view of the fish community (see Cappo *et al.* 2004 for review). However, broad contrasts with Area 17 (Broome to Cape Leveque) in Hutchins (2001) and the Canning bioregion (Travers *et al.* 2006, 2010) showed a much higher proportion of mobile, demersal, pelagic and semi-demersal predators in the James Price Point study area – and a lack of small sedentary and cryptic species. This must presumably be a result of the lack of coral reefs in the area sampled off James Price Point, the inability of the BRUVS to record smaller cryptic or nocturnal fishes (such as flatfishes), and the inability of traps and trawls to catch the larger ones (such as sharks).

Stereo-BRUVS were used by Watson *et al.* (2008) on the Burrup Peninsula in a different biogeographical region, but some robust comparisons can be made. Firstly, there were some notable similarities in the fauna seen in the two studies. Nine of the top 20 species seen off James Price Point were in the top 20 species recorded by Watson *et al.* (2008). Species such as the school mackerel *Scomberomorus queenslandicus*, false whiptail *Pentapodus porosus* and stripey seaperch *Lutjanus carponotatus* were broadly similar in their importance in both studies. Secondly, the James Price Point study area had a much higher abundance of "small pelagic" trevallies (*Selaroides*, *Atule*) and "large semi-demersal" predators (*Gnathanodon* trevallies, *Carcharhinus* sharks, *Scomberoides* queenfish), leiognathid ponyfish and nemipterid threadfin breams that inhabit bare substrata.

There were also some strong differences, with banded grunter *Terapou therap*s and caesionid fusiliers absent from James Price Point, and scarid parrotfish rarely recorded. The caesionid fusiliers are known to inhabit reefs dominated by corals, and the banded grunter prefer muddy/silty seafloors absent from the highly-scoured region off James Price Point (Cappo *et al.* 2007b). The lack of scarid parrotfishes was more likely due to the types of habitat sampled rather than a bias introduced by the BRUVS sampling technique. Field tests have shown that the use of bait produces much better discrimination of spatial groups, including herbivores, corallivores and other functional groups (Harvey *et al.* 2007, Cappo 2010), and Watson *et al.* (2008) recorded scarids on BRUVS in the Burrup peninsular.

There were also some important similarities amongst the associations between fishes and habitat detected in the two regions. Watson *et al.* (2008) found that fish assemblages were mainly distinguished between "bare" habitats and those with "epibenthos". Five types of substrata were recognised in that study (reef, sand-inundated reef, silty sand, coarse sand, reef/sand interface) and four of them had a significant relationship with the assemblage structure of fishes. Approximately 70% of the fish assemblage in silty and coarse sand areas comprised individuals in the families Terapontidae, Carangidae, Caesionidae and Nemipteridae. The "reef fish" assemblages included lethrinid emperors, lutjanid snappers and serranid cods. Approximately 70% of the assemblage in reef areas comprised individuals in the families Caesionidae, Nemipteridae, Carangidae, Labridae, Lethrinidae and Lutjanidae.

Sponge "gardens" and "macroalgae" were also recognised by Watson *et al.* (2008) in their analyses of stereo-BRUVS footage. Associations of fish with these

habitats were strongest for the coverage of algae, most notably for the redstripe tuskfish *Choerodon vitta*, the spangled emperor *Lethrinus nebulosus*, the bar-tailed goatfish *Upeneus tragula*, the grubfish *Parapercis xanthozona* and the palenose parrotfish *Scarus psittacus*. Numerous species were more abundant in habitats of the Burrup Peninsula dominated by stony corals and turf algae, especially black-tipped cod *Epinephelus fasciatus*, stripey seaperch *Lutjanus carponotatus*, monocle bream *Scolopsis monogramma*, moon wrasse *Thalassoma lunare* and ring-tailed surgeonfish *Acanthurus grammoptilus*. It is likely that some of these species inhabit the coral-dominated fringing reefs that were inaccessible to BRUVS in the James Price Point study area.

In summary, the simultaneous visual sampling of fish and their habitats has provided a baseline for predicting, monitoring and managing impacts on the ichthyofauna off James Price Point as well as adding to the understanding of the biodiversity of the poorly-known Kimberley region. The study area can be visualised in terms of latitude by deeper and shallower "garden" habitats, and by longitude, or cross-shelf increase in depth. Perhaps the simplest seafloor topography of all, the bare sandy habitat, intrudes inshore to James Price Point. The patterns in the fauna follow the distribution of species and assemblages known to occur elsewhere in the Indo-Pacific, but were most notable for the abundance of small planktivores and large predators. Comparison with the fauna at similar distance to shore in similar latitudes in the Great Barrier Reef lagoon showed significantly higher indices of diversity. In comparison with the Burrup Peninsula there were more small pelagic planktivores and more large semi-demersal predators. There was also an absence of some species normally associated with muddy seafloors (e.g. teraponid grunters) and fringing coral reefs (e.g. caesionid fusiliers and scarid parrotfish) that are common on BRUVS set elsewhere in regions with less extreme tidal ranges. It is possible that the baitfish-predator assemblages were enhanced by a higher nutrient status of north-western waters due to the Indonesian through-flow, tidal re-suspension and episodic upwellings offshore – but data is lacking. A lack of intense fishing pressure may also play a role. A multivariate analysis including the stereo-BRUVS data collected by Watson *et al.* (2008) from the Burrup Peninsula would enable much better interpretation of the faunal patterns recorded here for the James Price Point study area.

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Appendix 1

Summaries of fishes, sharks, rays and sea snakes sighted on BRUVS. The total number recorded (N.fish) is shown as a percentage of the 7108 individuals recorded. The 50th, 75th and 95th percentiles in distribution of the count data are shown for each species. For example, 50% of the BRUVS sites had 2, or less, individuals of the ubiquitous school mackerel *Scomberomorus queenslandicus*, and only 5% of the sites had more than 5 individuals seen in the field of view at one time. The number of BRUVS sites on which the species occurred (N.sites) is also shown as a percentage of the 154 sites sampled in the vicinity of James Price Point. Genera listed as important to fisheries by Newman *et al.* (2004) and Williamson *et al.* (2006) are highlighted in bold.

Order/Family	Scientific Name	Common Name	N.fish	%abun	q50%	q75%	q95%	N.sites	%sites
Carcharhiniformes									
	Hemigaleidae								
	<i>Hemipristis elongata</i>	Fossil shark	2	0	0	0	0	2	1.3
Carcharhinidae									
	<i>Carcharhinus dussumieri</i>	White cheek sharks	8	0.1	0	0	0	7	4.5
	<i>Carcharhinus tilstoni</i>	Australian blacktip shark	35	0.5	0	0	1	32	20.8
	<i>Carcharhinus amblyrhynchos</i>	Grey reef shark	9	0.1	0	0	0	3	1.9
	<i>Carcharhinus melanopterus</i>	Blacktip reef shark	1	0	0	0	0	1	0.6
	<i>Galeocerdo cuvier</i>	Tiger shark	2	0	0	0	0	2	1.3
	<i>Rhizoprionodon taylori</i>	Milk shark	6	0.1	0	0	0	6	3.9
	<i>Negaprion acutidens</i>	Lemon shark	2	0	0	0	0	2	1.3
									
	<i>Sphyrna mokarran</i>	Great hammerhead shark	11	0.2	0	0	1	11	7.1
Orectolobiformes									
Hemiscylliidae									
	<i>Chiloscyllium punctatum</i>	Catshark	4	0.1	0	0	0	4	2.6
Stegostomatidae									
	<i>Stegostoma fasciatum</i>	Leopard shark	6	0.1	0	0	0	6	3.9

Order/Family	Scientific Name	Common Name	N.fish	%abun	q50%	q75%	q95%	N.sites	%sites
Ginglymostomatidae									
<i>Rajiformes</i>	<i>Nebrius ferrugineus</i>	Nurse shark	2	0	0	0	0	2	1.3
Rhynchobatidae									
	<i>Rhynchobatus djiddensis</i>	White-spotted Shovelnose	14	0.2	0	0	1	14	9.1
Rhinidae									
	<i>Rhina ancylostoma</i>	Shark ray	3	0	0	0	0	3	1.9
<i>Myliobatiformes</i>									
Dasyatidae									
	<i>Himantura uarnak</i>	Stingray	1	0	0	0	0	1	0.6
	<i>Himantura toshi</i>	Whip ray	1	0	0	0	0	1	0.6
	<i>Himantura jenkinsii</i>	Whip ray	6	0.1	0	0	0	5	3.2
	<i>Dasyatis kuhlii</i>	Masked ray	1	0	0	0	0	1	0.6
	<i>Pastinachus sephen</i>	Cowtail Stingray	3	0	0	0	0	3	1.9
<i>Anguilliformes</i>									
Muraenidae									
	<i>Gymnothorax pseudothyrsoides</i>	Moray eel	1	0	0	0	0	1	0.6
	<i>Gymnothorax pale sp</i>	Moray eel	2	0	0	0	0	1	0.6
<i>Elopiformes</i>									
Elopidae									
	<i>Elops hawaiiensis</i>	Giant herring	10	0.1	0	0	1	9	5.8
<i>Clupeiformes</i>									
Clupeidae									
	<i>Herkloisichthys blackburni</i>	Blackburn's sardine	366	5.1	0	0	5.7	14	9.1
<i>Aulopiformes</i>									

Order/Family	Scientific Name	Common Name	N.fish	%abun	q50%	q75%	q95%	N.sites	%sites
Synodontidae									
	<i>Saurida sp</i>	Lizardfish	3	0	0	0	0	3	1.9
Siluriformes									
Ariidae									
	<i>Arius thalassinus</i>	Giant salmon catfish	4	0.1	0	0	0	4	2.6
Scorpaeniformes									
Scorpaenidae									
	<i>Pterois volitans</i>	Lionfish	2	0	0	0	0	2	1.3
Perciformes									
Serranidae									
	<i>Epinephelus bilobatus</i>	Frostback cod	41	0.6	0	0	1.3	30	19.5
	<i>Epinephelus coioides</i>	Goldspot cod	4	0.1	0	0	0	4	2.6
	<i>Epinephelus multinotatus</i>	White-blotched cod	3	0	0	0	0	2	1.3
	<i>Epinephelus rivulatus</i>	Chinaman cod	1	0	0	0	0	1	0.6
	<i>Epinephelus quoyanus</i>	Wire-netting cod	1	0	0	0	0	1	0.6
	<i>Epinephelus merra</i>	Wire-netting cod	6	0.1	0	0	0	5	3.2
	<i>Plectropomus maculatus</i>	Bar-cheeked coral trout	23	0.3	0	0	1	17	11
Sillaginidae									
	<i>Sillago sp</i>	Whiting	55	0.8	0	0	2.3	27	17.5
Echeneidae									
	<i>Echeneis naucrates</i>	Suckerfish	41	0.6	0	0	1.3	31	20.1
Glucosomatidae									
	<i>Glucosoma magnificum</i>	Pearl perch	6	0.1	0	0	0	4	2.6

Order/Family	Scientific Name	Common Name	N.fish	%abun	q50%	q75%	q95%	N.sites	%sites
Rachycentridae									
	<i>Rachycentron canadum</i>	Cobia	16	0.2	0	0	1	13	8.4
Carangidae									
	<i>Carangoides malabaricus</i>	Malabar trevally	7	0.1	0	0	0	3	1.9
	<i>Carangoides chrysophrys</i>	Club-nosed trevally	2	0	0	0	0	2	1.3
	<i>Carangoides fulvoguttatus</i>	Gold-spot trevally	59	0.8	0	0	2	35	22.7
	<i>Carangoides hedlandensis</i>	Bump-nosed trevally	95	1.3	0	1	3	53	34.4
	<i>Carangoides talamparoides</i>	White-tongued trevally	2	0	0	0	0	2	1.3
	<i>Carangoides coeruleopinnatus</i>	Onion trevally	1	0	0	0	0	1	0.6
	<i>Carangoides gymnotethus</i>	Bludger trevally	3	0	0	0	0	3	1.9
	<i>Caranx ignobilis</i>	Giant trevally	29	0.4	0	0	1	13	8.4
	<i>Caranx bucculentus</i>	Blue-spotted trevally	5	0.1	0	0	0	2	1.3
	<i>Gnathanodon speciosus</i>	Golden trevally	172	2.4	0	1	6	45	29.2
	<i>Scomberoides commersonnianus</i>	Queenfish	31	0.4	0	0	1	29	18.8
	<i>Seriolina nigrofasciata</i>	Black-banded kingfish	8	0.1	0	0	0	7	4.5
	<i>Selar boops</i>	Ox-eye scad	246	3.5	0	0	4.3	14	9.1
	<i>Selaroides leptolepis</i>	Gold-lined trevally	1341	18.9	4	10	35	109	70.8
	<i>Atule mate</i>	Yellow-tail scad	1109	15.6	1	7.8	30	86	55.8
Leiognathidae									
	<i>Leiognathus longispinis</i>	Smithurst's ponyfish	329	4.6	0	1	12.7	40	26
Lutjanidae									
	<i>Lutjanus vitta</i>	Striped seaperch	61	0.9	0	0	0	7	4.5
	<i>Lutjanus sebae</i>	Red Emperor	3	0	0	0	0	2	1.3
	<i>Lutjanus erythropterus</i>	Crimson sea perch	7	0.1	0	0	0	2	1.3
	<i>Lutjanus lemniscatus</i>	Dark-tailed sea perch	2	0	0	0	0	2	1.3
	<i>Lutjanus carponotatus</i>	Stripe seaperch	95	1.3	0	1	3	40	26
	<i>Lutjanus fulvislamma</i>	Black-spot sea perch	2	0	0	0	0	1	0.6
	<i>Symphorus nematophorus</i>	Chinaman fish	1	0	0	0	0	1	0.6
Haemulidae									

Order/Family	Scientific Name	Common Name	N.fish	%abun	q50%	q75%	q95%	N.sites	%sites
Lethrinidae	<i>Plectorhinchus schotaf</i>	Minstrel Sweetlip	3	0	0	0	0	3	1.9
	<i>Diagramma pictum</i>	Slatey bream/Painted sweetlips	29	0.4	0	0	1	22	14.3
									
Nemipteridae	<i>Lethrinus punctulatus</i>	Blue-spotted emperor	519	7.3	0	2	20.3	51	33.1
	<i>Lethrinus olivaceus</i>	Long-nosed emperor	3	0	0	0	0	3	1.9
	<i>Lethrinus "laticaudis/frenatus"</i>	Blue-lined emperor	3	0	0	0	0	3	1.9
									
	<i>Nemipterus peronii</i>	Peron's threadfin bream	5	0.1	0	0	0	4	2.6
	<i>Nemipterus furcosus</i>	Rosy threadfin bream	174	2.4	0	0	7	33	21.4
	<i>Scolopsis monogramma</i>	Monocle bream	29	0.4	0	0	1	22	14.3
	<i>Scolopsis marginifer</i>	Pearl-streaked monocle bream	1	0	0	0	0	1	0.6
	<i>Pentapodus porosus</i>	False whiptail	1078	15.2	6	12	16.3	119	77.3
	<i>Pentapodus vitia</i>	Western butterflyfish	73	1	0	0	3	28	18.2
									
	<i>Upeneus moluccensis</i>	Gold-band goatfish	1	0	0	0	0	1	0.6
	<i>Upeneus tragula</i>	Bar-tailed goatfish	29	0.4	0	0	1	13	8.4
	<i>Parupeneus indicus</i>	Indian goatfish	3	0	0	0	0	3	1.9
Chaetodontidae									
	<i>Coradion chrysozonus</i>	Orange-banded coralfish	9	0.1	0	0	0.3	8	5.2
	<i>Chelmon marginalis</i>	Margined coralfish	21	0.3	0	0	1	13	8.4
	<i>Chaetodon aureofasciatus</i>	Golden-striped butterflyfish	1	0	0	0	0	1	0.6
Pomacanthidae									
Terapontidae	<i>Chaetodontoplus duboulayi</i>	Scribbled angelfish	49	0.7	0	0	2	33	21.4
Labridae									
	<i>Terapon jarbua</i>	Crescent perch	1	0	0	0	0	1	0.6
									
	<i>Anampses lennardi</i>	Blue and yellow wrasse	2	0	0	0	0	1	0.6

Order/Family	Scientific Name	Common Name	N.fish	%abun	q50%	q75%	q95%	N.sites	%sites
Scaridae	<i>Choerodon cephalotes</i>	Purple tuskfish	46	0.6	0	0	1.3	28	18.2
	<i>Choerodon cauteroma</i>	Blue-spotted tuskfish	37	0.5	0	0	1	27	17.5
	<i>Choerodon vitta</i>	Red-stripe tuskfish	15	0.2	0	0	1	9	5.8
	<i>Choerodon schoenleinii</i>	Black-spot tuskfish	36	0.5	0	0	2	20	13
	<i>Choerodon cyanodus</i>	Blue tuskfish	43	0.6	0	0	2	25	16.2
Pomacentridae	<i>Scarus ghobban</i>	Blue-barred parrotfish	1	0	0	0	0	1	0.6
	<i>Scarus schlegelii</i>	Schlegel's parrotfish	1	0	0	0	0	1	0.6
	<i>Abudefduf septemfasciatus</i>	Banded sergeant	2	0	0	0	0	2	1.3
Pinguipedidae	<i>Abudefduf sexfasciatus</i>	Scissortail sergeant	3	0	0	0	0	2	1.3
	<i>Pomacentrus wardi</i>	Ward's damselfish	2	0	0	0	0	1	0.6
Ephippidae	<i>Parapercis multiplacata</i>	Red-banded grubfish	68	1	0	0	2.3	38	24.7
	<i>Parapercis sp</i>	Grubfish	1	0	0	0	0	1	0.6
Siganidae	<i>Platax batavicus</i>	Hump-headed batfish	2	0	0	0	0	2	1.3
	<i>Platax teira</i>	Round-faced batfish	1	0	0	0	0	1	0.6
	<i>Platax orbicularis</i>	Narrow-banded batfish	1	0	0	0	0	1	0.6
	<i>Zabidius novemaculeatus</i>	Short-finned batfish	1	0	0	0	0	1	0.6
	<i>Siganus sp</i>	Rabbitfish	1	0	0	0	0	1	0.6
Acanthuridae	<i>Siganus argenteus</i>	Spinefoot	20	0.3	0	0	0	5	3.2
	<i>Acanthurus dussumieri</i>	Ornate surgeon-fish	4	0.1	0	0	0	3	1.9
Sphyrnidae	<i>Sphyrna jello</i>	Pick-handle barracuda	14	0.2	0	0	1	14	9.1

Order/Family	Scientific Name	Common Name	N.fish	%abun	q50%	q75%	q95%	N.sites	%sites
Scombridae	<i>Sphyræna barracuda</i>	Great barracuda	6	0.1	0	0	0	6	3.9
									
	<i>Scomberomorus semifasciatus</i>	Broad-barred mackerel	1	0	0	0	0	1	0.6
	<i>Scomberomorus commerson</i>	Spanish mackerel	6	0.1	0	0	0	6	3.9
	<i>Scomberomorus queenslandicus</i>	School mackerel	327	4.6	2	3	5	138	89.6
Tetraodontiformes	<i>Cybiosarda elegans</i>	Watson's leaping bonito	13	0.2	0	0	1	10	6.5
Balistidae									
	<i>Abalistes stellatus</i>	Starry triggerfish	29	0.4	0	0	1.3	20	13
Monacanthidae									
	<i>Monacanthus chinensis</i>	Fan-bellied leatherjacket	10	0.1	0	0	1	10	6.5
	<i>Paramonacanthus otisensis</i>	Leatherjacket	36	0.5	0	0	2	20	13
Ostraciidae									
	<i>Cyclichthys orbicularis</i>	Boxfish	1	0	0	0	0	1	0.6
Tetraodontidae									
	<i>Torquigener sp</i>	Pufferfish	1	0	0	0	0	1	0.6
	<i>Torquigener pallimaculatus</i>	Orange-spotted toadfish	2	0	0	0	0	2	1.3
	<i>Lagocephalus scleratus</i>	Silver toadfish/Norwest blowie	2	0	0	0	0	2	1.3
	<i>Feroxodon multistriatus</i>	Many-striped pufferfish	5	0.1	0	0	0	5	3.2
Diodontidae									
	<i>Tragulichthys jaculiferus</i>	Globefish	2	0	0	0	0	2	1.3
Reptilia: Squamata									
									
	<i>Aipysurus laevis</i>	Olive sea snake	22	0.3	0	0	1	19	12.3
Hydrophiidae	<i>Hydrophis ornatus</i>	Ornate sea snakes	1	0	0	0	0	1	0.6

Are Western Australian waters the least productive waters for finfish across two oceans? A review with a focus on finfish resources in the Kimberley region and North Coast Bioregion

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Abstract

The marine ecosystems of Western Australia, including those in the Kimberley, are classified as being of moderate to low productivity. This is primarily a consequence of the influence of the Leeuwin Current, the eastern boundary current that flows poleward delivering warm, low nutrient waters, and only sporadic short-term upwelling events to shelf habitats off the Western Australian coast. This, coupled with little riverine inflow from old weathered terrestrial systems, results in low levels of primary and secondary production in habitats along most of the coast. The consequence is that finfish fisheries in the Kimberley and throughout the State typically land a diverse range of long-lived species with low levels of productivity, resulting in relatively low levels of sustainable catches. The consequences for monitoring, management and stakeholder aspirations are presented. Additional challenges for finfish fisheries in the Kimberley and North Coast finfish fisheries are also discussed.

Keywords: fisheries, finfish, productivity, Western Australia, Kimberley, North Coast Bioregion

Introduction

Western Australia's coast extends more than 12,800 kilometres from the Northern Territory border, west to the South Australian border. The waters of Western Australia extending out to the Australian Exclusive Economic Zone (EEZ) represent approximately one third of the Australian EEZ, or approximately 2 million km² of ocean between 10°–40°S. Within these waters there are more than 20 State-managed commercial finfish fisheries that operate from the North Coast Bioregion (which includes the Kimberley) targeting tropical species such as barramundi, red emperor and Spanish mackerel through to southern fisheries targeting species such as pilchards on the West Australian side of the Great Australian Bight (DoFWA 2011, see also Fletcher and Santoro (2010) for details). Throughout this range there are also extensive recreational fisheries including recreational-only fisheries off the coast of Perth and within the Shark Bay World Heritage Area and areas of high levels of recreational effort such as Roebuck Bay immediately south of Broome.

In addition to the State-managed fisheries, there are also fisheries managed by the Australian Fisheries Management Authority (AFMA, see Wilson *et al.* (2010) for details), including three deep-water trawl fisheries that also capture finfish off the coast of Western Australia; the North West Slope Trawl Fishery off the Kimberley and Pilbara Coasts; the Western Deepwater

Trawl Fishery off the Gascoyne and West Coasts; and the Great Australian Bight Trawl Fishery along the South Coast. There are also two Joint Authority fisheries (the Joint Authority Northern Shark Fishery which operates in the Kimberley and the Joint Authority Southern Demersal Gillnet and Demersal Longline Fishery, (see Fletcher and Santoro (2010) for details) for which management responsibility is shared between the Commonwealth, State and adjacent Territories. Australia is also a member of the Indian Ocean Tuna Commission (IOTC, www.iotc.org) and Australian-flagged vessels can operate within the waters of the Australian EEZ off the Western Australia coast to target tuna, billfish and other permitted species.

The extensive ocean area off the West Australian coast and large number of fisheries can lead to the perception that there are extensive finfish fishery resources to be exploited. However, the total finfish (*i.e.* scalefish and elasmobranchs) production for Western Australia is globally modest (Lenanton *et al.* 2007). For example, since 1988/89 annual finfish catches for all State-managed fisheries have fluctuated between 2,500 tonnes to 24,000 tonnes, averaging approximately 15,000 metric tonnes per year (t.yr⁻¹) over the last decade, with a recent decline (Fig. 1). The average production is approximately 130 t.yr⁻¹ per 100 km of coastline, not including recreational fisheries. Peak catches were recorded during the period 1996–1998, at the height of the southern purse-seine fishery for small, relatively short-lived pelagic species (mainly pilchards, *Sardinops sagax*) immediately



Figure 1. Map of Western Australia showing the extensive coastline, latitudinal range and the four marine and two inland Bioregions in the State. Source: Fletcher & Santoro (2010). The Kimberley area is approximately north of 20°S and east of 120°E.

prior to the collapse of the fishery due to the herpes virus in the mid to late 1990s (Whittington *et al.* 2008), which resulted in biomass reductions of up to 75% (Gaughan *et al.* 2000). The Kimberley fisheries, while increasing, have only recently exceeded 1,000 metric tonnes t.yr⁻¹.

In addition to State managed fisheries, fisheries managed by AFMA have also reported modest catches. For example, the North West Slope Trawl Fishery targets invertebrates but has reported approximately 130 t.yr⁻¹ of fish (as discarded bycatch) between 2000 and 2008 (Emery *et al.* 2009a). The Western Deepwater Trawl Fishery, which targets finfish and invertebrates, has reported total finfish catches of up to 320 t.yr⁻¹ (in 2001); however more recent catches have declined with less than 20 t.yr⁻¹ reported between 2004 and 2006 (Emery *et al.* 2009b). The most recent data available (Wilson *et al.* 2010) shows that the annual retained scalefish catch from these fisheries is well below 100 t.yr⁻¹. The highest annual catch reported for an individual species was 885 tonnes of deepwater flathead landed by the Great Australian Bight Trawl sector in 2009/10. However the area of intensive fishing straddles the WA/SA border, and the proportion of this catch taken in West Australian waters was not reported. Declines in fishing effort have also been reported in other AFMA managed fisheries operating off the coast of Western Australia (Table 1). Finfish catches by the Joint Authority fisheries operating off the coast of Western Australia are included in the catches reported in the State (see Fletcher & Santoro 2010). Thus, the combined catches of these Commonwealth managed fisheries adds a relatively

small amount to the total catches in waters off Western Australia.

Historically, trawlers from distant water fishing nations also operated off the coast of Western Australia, principally in the Kimberley and Pilbara areas between 1980 and 1990 (Nowara & Newman, 2001). While these trawlers operated throughout extensive areas of the North Coast Bioregion, the limited data available indicates that catches were modest and not likely to be profitable to sustain these fleets. Since the mid 1990s, the waters of the Australian EEZ have been reserved exclusively for Australian fishing vessels, only limited Commonwealth trawling has been reported in the North Coast Bioregion, producing modest catches (Table 1).

Additionally, many of the State managed fisheries operating off Western Australia either have a recent history of declining catches (*e.g.* WCDSF, Wise *et al.* 2007; Fairclough *et al.* 2010), and/or reduced levels of effort due to risks to biological sustainability of fish stocks and resources (Fairclough *et al.* 2010; Newman *et al.* 2010c), while the Commonwealth managed fisheries are characterised by relatively high levels of unused (latent) effort or licenses (*e.g.* Rodgers *et al.* 2010; Sampaklis *et al.* 2010). Thus most commercial finfish fisheries operating in WA waters are considered fully-exploited, or have large amounts of entitlement not being used likely due to the non-viability of profitable fishing.

This paper aims to define the productivity and fisheries in Western Australia in a wider context with a focus on finfish fisheries operating in the Kimberley region. The relatively low productivity of finfish resources are discussed in relation to the implications for monitoring, management and stakeholders in the State. Additional challenges for finfish resources and exploitation in the Kimberley and North Coast Bioregion are also presented.

How large are WA fisheries relative to other locations?

Three examples have been selected to put the total catches and productivity of finfish resources of WA in a broader context. Barramundi (*Lates calcarifer*) are captured throughout the Kimberley and northern Western Australia, throughout the Northern Territory and tropical Queensland. Commercial catches in Western Australia from approximately 4,000 km of coastline have varied between 27 and 60 t.yr⁻¹ since 1999 (Newman *et al.* 2010b). In comparison, the Northern Territory landed 588–665 t.yr⁻¹ and Queensland 880–1,071 t.yr⁻¹ (2006–07 to 2008–09 catches, ABARE–BRS 2010). The WA fishery is approximately one order of magnitude smaller than other barramundi fisheries in Australia despite an extensive coastline.

Pink snapper (*Pagrus auratus*) is a demersal species targeted by both commercial and recreational anglers in Western Australia. This species is also found throughout the temperate and subtropical regions of Australia and New Zealand. In WA pink snapper are fished from north of Carnarvon (Fig. 1) to the south Australian border (at least 2,800 km). The total West Australian catch of pink snapper is approximately 600 t.yr⁻¹ (Fletcher & Santoro 2010). In comparison, the New Zealand Snapper Area One (SNA1) fishery (north of Auckland) has an annual

Table 1

Summary of recent catch data for Australian Fisheries Management Authority (AFMA) managed fisheries operating in the waters off the coast of Western Australia. (t, metric tonnes; AFZ, Australian Fishing Zone).

Fishery	Relevant component to Western Australia	Recent catch data	Comment	Source
Small Pelagic	B-zone	Not available	Too few vessels operating to release data for B-zone	Wilson <i>et al.</i> 2010, pp 131–146; www.afma.gov.au
Great Australian Bight Trawl Sector	Operates between 115°08'06"E Cape Leeuwin WA) and 138°08'05"E (Cape Jervis, SA)	2007/08 catch 3,712 t; 2008/09 catch 1,630 t; 2009/10 catch 1,556 t. 10 permit holders, 4 active in 09/10.	Proportion of catches taken in waters off Western Australia not reported	Wilson <i>et al.</i> 2010, pp 232–249; www.afma.gov.au
Western Skipjack Tuna	From 142°30'E (Cape York), west to the South Australian Border (Encompassing waters of the Gulf of Carpentaria, Northern Territory, Western Australia and South Australia)	406 searching hours was reported from this fishery in 2008/09. Total catch, 885 t. 13 permit holders but only 2 active in 2008/09.	Very low levels of activity in this fishery.	Wilson <i>et al.</i> 2010, pp 411–421; www.afma.gov.au
Western Tuna and Billfish	From 142°30'E (Cape York), west to the South Australian Border (Encompassing waters of the Gulf of Carpentaria, Northern Territory, Western Australia and South Australia)	2009, 93 permits but only 3 active. Catch, 455 t.	Between 2004 and 2009, 144.7 t of minor by-product retained, and 57,727 individuals (mostly sharks) discarded.	Wilson <i>et al.</i> 2010, pp 433–458; www.afma.gov.au
North West Slope Trawl	From 114°E to 125°E, between 200m isobath and AFZ outer boundary	2005/06 to 2008/09 136 t of minor byproduct retained, 22.6 t discarded. 7 permit holders but only 2 active in 2008/09.	Retained catch of scalefish very small.	Wilson <i>et al.</i> 2010, pp 119–130; www.afma.gov.au
Western Deepwater Trawl	From 115°08'E off the south coast to 114°E off the north coast.	2004/05 to 2008/09 72 t scalefish retained, 0.7 t discarded. 11 permit holders but only 1 active in 2008/09.	Retained catch of scalefish very small.	Wilson <i>et al.</i> 2010, pp 337–349; www.afma.gov.au

total allowable catch (TAC) of 7,500 t.yr⁻¹ (<http://fs.fish.govt.nz/Page.aspx?pk=7&tk=37&sc=SNA>). The total snapper TAC for New Zealand is more than 10,000 t.yr⁻¹ (<http://fs.fish.govt.nz/Page.aspx?pk=7&tk=37&sc=SNA>) for a 15,000 km coastline (fs.fish.govt.nz/Page.aspx?pk=45&tk=464). Western Australia catches of pink snapper are more than an order of magnitude lower than those for New Zealand, highlighting massive differences in productivity.

In a more extreme example, the total Western Australian catches of small pelagic fishes (mainly pilchards, *Sardinops sagax*) by the South Coast purse-seine fishery in its peak (1986–1997) was approximately 9,000 t.yr⁻¹ (Molony & Lai 2010). In contrast, catches of an ecologically similar species, the Peruvian anchovy, *Engraulis ringens*, have ranged between 6.2 and 10.7 million t.yr⁻¹ between 2003 and 2007 (FAO 2009); Western Australian record catches of small pelagic fishes could be taken within a single day in the Peruvian anchovy fishery off the west coast of South America between Valparaiso, Chile and Chimbote, Peru (approximately 3,200 km), making West Australian catches insignificant in comparison (Lenanton *et al.* 1991). In addition, comparisons with the adjacent South Australian fishery

are notable. The South Australian Sardine Fishery has had annual catches between 29,854 and 31,577 t.yr⁻¹ since 2007 (Ward *et al.* 2010).

Why the relatively small scalefish fisheries in Western Australia?

These three examples demonstrate that the Western Australian catches of many finfish species are relatively modest compared to catches of the same or similar species in other parts of Australia and the world. This raises the question; with such an extensive coastline and so much water, why are the catches so low? There are several reasons for this.

Globally, waters off Western Australia, including the Kimberley region, are generally of low to moderate primary productivity (Pearce *et al.* 2000), internationally classified as Class II (moderate: 150–300 gC.m⁻².yr⁻¹) or Class III (Low: <150 gC.m⁻².yr⁻¹) productivity systems (McGinley 2008a, b, c). The exception is the Class I high productivity (>300 gC.m⁻².yr⁻¹) ecosystem of northern Australia, from Cape Londonderry (Western Australia) east to Cape York (Queensland) (McGinley 2008d). However, this ecosystem accounts only for some 250 km (or 2%) of the coastline of Western Australia. The rest of

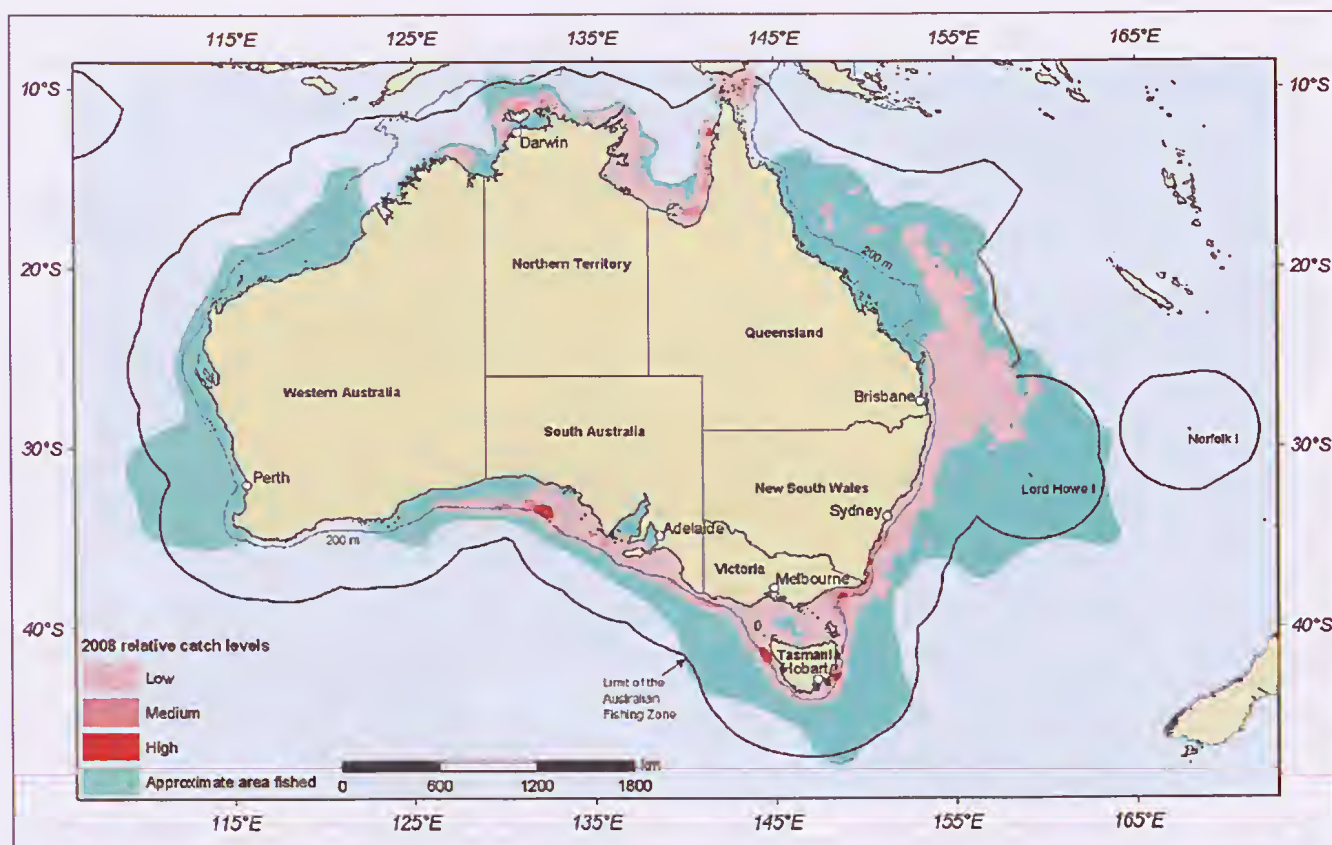


Figure 2. The relatively low levels of catches by Commonwealth Fisheries in waters adjacent to Western Australia are clearly shown by a national comparison of relative catch levels. Also note the areas where no Commonwealth catch (and therefore effort) was reported in 2008, despite these areas being open to a range of Commonwealth fisheries. Sources: Wilson *et al.* (2010) and www.daff.gov.au/_data/assets/image/0009/1373292/Relative-catch-levels.jpg

the West Australian waters are of low to moderate primary productivity, including the marine waters of the Kimberley.

The southward flowing Leeuwin Current dominates the oceanography along the Western Australian shelf (Lenanton *et al.* 1991, 2009). This low-nutrient current, which originates in the tropical Kimberley area, of Western Australia (Cresswell and Domingues 2009), runs poleward and limits the productivity of shelf waters, especially in temperate Western Australia (Godfrey & Ridgeway 1985; Caputi *et al.* 1996; Muhling *et al.* 2008). While there are localised and sporadic small-scale upwelling events (Lenanton *et al.* 2009), there is an absence of large, predictable, nutrient rich upwelling systems that are typical of other shelf systems along the eastern sides of ocean basins (Lenanton *et al.* 1991; Pearce 1991; *e.g.* the Canary Current, north-western Africa; the California Current, western North America, especially off California and Oregon; the Humboldt Current, north-western South America, especially off Peru and Chile).

Secondly, there is limited terrestrial input into ocean productivity off the Western Australian coast. Western Australia is the oldest part of the Gondwana land mass presently above sea level (Fig. 3), with ages of the continental crust in Western Australia ranging between 545 ma (million years of age) and 4,560 ma (en.wikipedia.org/wiki/Natural_history_of_Australia), allowing a long period of time for weathering and

erosion to occur. This is evidenced by the relatively modest peaks and extensive low-lying areas in Western Australia, particularly in the north. The highest peak in Western Australia is in the north of the State, Mount Meharry in the Hamersley Range, approximately 1,250 m above sea level (Geosciences Australia, www.ga.gov.au/geodesy/ngdb). In the South West, the highest point is Bluff Knoll (1,070 m) in the Stirling Ranges. In contrast, the continental crust is much younger in Eastern Australia (Fig. 3) as the plate is being formed in the "rim of fire" in the Pacific Ocean off eastern Australia. As a result, in countries in the Pacific Ocean like New Zealand, Vanuatu and New Guinea, and in eastern Australia where the plate is much younger than in Western Australia, mountains are relatively high, some thousands of metres tall. Some mountains are high enough to gather snow at certain times and some even support permanent glaciers (*e.g.* in New Guinea, Hope *et al.* 1976).

A consequence of this long-term weathering is that the soils are extremely nutrient poor in many areas of Western Australia. These soils have been classified as Old, Climatically Buffered, Infertile Landscapes (OCBILs, Hopper 2009). As a consequence, there are very limited areas of high terrestrial productivity. For example, there are no extensive forests in the Kimberley region of Western Australia as there are in similar latitudes in North Queensland. Much of the northern areas of

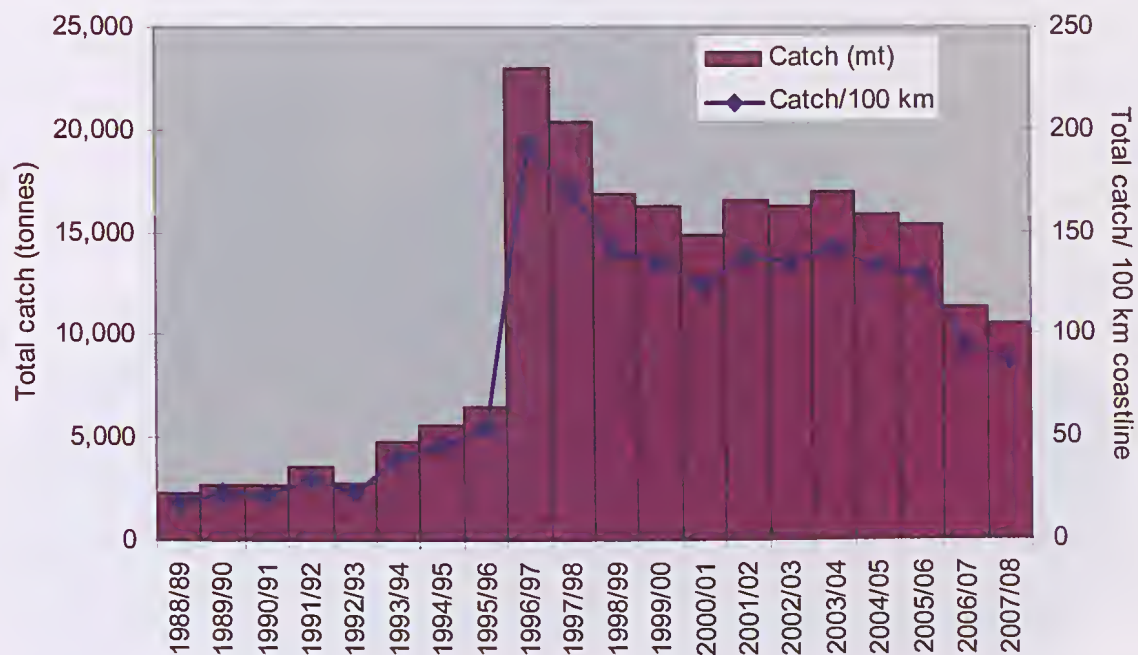


Figure 3. Total finfish production by Western Australia, 1988/89 to 2007/08. Source: Australian Bureau of Agricultural and Resource Economics (ABARE), www.abare.gov.au.

Western Australia are desert with low-lying scrub. In the south, while there are forests, they are not as extensive as in other places and are limited to the plains between the Indian Ocean and the relatively low Stirling ranges.

Additionally, with few mountains and extensive areas of relatively flat land, there are few catchments that support large rivers. The entire coastline of Western Australia has relatively few river systems, few wetlands and few coastal embayments (*e.g. cf.* Queensland). There are extensive areas of the coastline where no river crosses. For example, between Broome and Port Hedland there is approximately 400 kilometres of coastline without a permanent river that crosses the coast. Similarly, there are no rivers that cross anywhere along more than 500 km of coastline between Esperance and the Western Australia-South Australia border. These great distances of coastline without river systems highlight the low terrestrial input to the oceans, and thus low oceanic productivity off Western Australia.

The low primary productivity results in modest concentrations of zooplankton. Comparisons with Southern Africa and South America show that secondary productivity in Western Australia is relatively low, between 50 and 200 mg.m⁻³, including waters of the Kimberley region (Pearce *et al.* 2000). In other upwelling systems (*e.g.* South America), secondary productivity can be greater than 500 mg.m⁻³, more than an order of magnitude higher.

The low levels of primary and secondary productivity limit scalefish production. Large upwelling systems typically support very large fisheries (hundreds of thousands of tonnes), including demersal scalefish fisheries. In the absence of large, regular upwelling systems (Pearce *et al.* 2000), the fisheries production in Western Australia is limited (Lenanton *et al.* 1991, Caputi *et al.* 1996, Muhling *et al.* 2008). Many demersal scalefish

fisheries typically produce in the order of less than two thousand t.yr⁻¹ (Lenanton *et al.* 1991, 2007; Fletcher & Santoro 2010). Total production of short-lived pelagic species, such as pilchard (*Sardinops sagax*), are also relatively small, with peak annual catches being less than 10,000 t.yr⁻¹, insignificant to catches of similar species in the Humboldt Current off Peru (Lenanton *et al.* 1991).

An ecological consequence of limited productivity is high diversity (Hopper *et al.* 2009); no single species tends to dominate nutrient poor environments such as much of the marine systems in Western Australia. For example, in the Northern Demersal Scalefish Fishery at least 56 species of fish have been captured in traps, with more than 130 species recorded from video surveys (Newman *et al.* in review). Similarly, in the West Coast Demersal Scalefish Fishery more than 100 species have been reported in the catch of recreational and commercial fishers (Fairclough *et al.* 2010). With high diversity, the stock sizes of individual species are relatively small. In Western Australia, stock sizes of many demersal species are estimated in the hundreds or low thousands of tonnes per species (Fletcher & Santoro 2010) including in the Kimberley region and the North Coast Bioregion (Newman *et al.* 2010c).

An evolutionary consequence of a low productivity environment with high diversity is a shift towards long-lived species with a long period of maturity. In Western Australia, many demersal species supporting commercial and recreational fisheries have longevities greater than 25 years (Wise *et al.* 2007), including species in the Kimberley and North Coast Bioregion (*e.g.* *Lutjanus sebae*, 40 years (Newman *et al.* 2010a), *Pristipomoides multidens*, 30 years (Newman and Dunk 2003)) and temperate species (*e.g.* *Glaucosoma hebraicum*, 41 years (Hesp *et al.* 2002), *Pagrus auratus*, 41 years (Norris & Crisafulli 2010)).

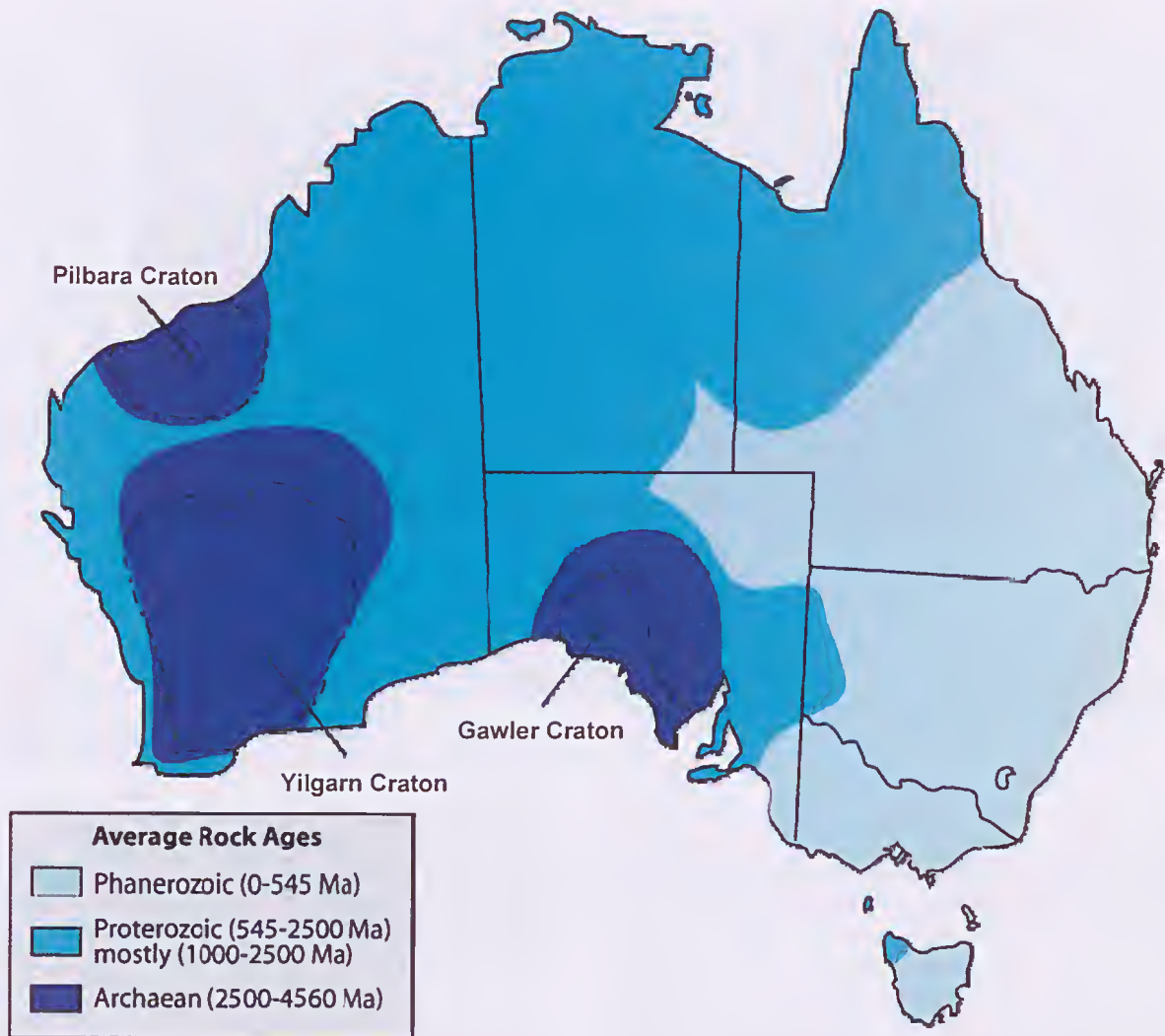


Figure 4. Map of Australia showing the ages (in millions of years, ma) of the continental crust. Source: en.wikipedia.org/wiki/Natural_history_of_Australia.

One hypothesis for evolution of a high longevity is to allow for a long period of sexual maturity. In environments with low productivity, a long period of maturity maximises the likelihood of reproduction during favourable conditions for a given species. Many of the demersal species in Western Australia mature at between 3–7 years (see Hesp *et al.* 2002; Newman & Dunk 2003; Newman *et al.* 2010a; DoFWA 2011), allowing these species up to several decades of reproductive activity. This allows an increased chance of spawning during periods where environmental conditions are favourable for a given species (Lenanton *et al.* 2009).

A further consequence of low productivity and long periods of sexual maturity is that there is typically variable recruitment. For example there have only been two (1999 and 2007) above average recruitment events in over a decade of monitoring pink snapper recruitment in temperate Cockburn Sound (C. B. Wakefield pers. comm.) and sub-tropical Shark Bay (G. J. Jackson pers. comm.). Additionally, variable recruitment resulting in strong recruitment every five to ten years may be sustaining a stock and therefore the fishery in some regions (e.g. *Glaucosoma hebraicum* Wise *et al.* 2007;

Lenanton *et al.* 2009). As a consequence relatively few age classes may dominate catches that support much of the fishery exploitation (Wise *et al.* 2007).

Implications of low productivity finfish resources in Western Australian

Applying fisheries management over small stocks with these types of population dynamics means that there is only scope for a modest total sustainable fishery production on many stocks and resources. This is not a new finding. In the early 1900s, the survey vessel “*The Rip*” reported that with large areas of barren land, there was unlikely to be large finfish fisheries to be sustained in Western Australian waters (Oxley 1904).

The management implications of low productivity and small-scale fisheries are clear. Firstly the total productivity in terms of catches for many species of finfish will be relatively low. In WA, few species of scalefish have supported catches over 500 t.yr⁻¹ (see Fletcher & Santoro 2010) with the exception of pilchards and some other shorter-lived species (e.g. Australian herring, *Arripis georgianus*).

Given the high diversity, it is unlikely that significant large new fishery resources will be identified that could support large commercial or recreational fisheries. Most finfish fisheries are multi-species fisheries, typically relying on 10–15 species to account for 90% of catches (see Fletcher & Santoro 2010), with year-to-year variability among species that dominate catches. This applies to both State-managed and Commonwealth fisheries operating off the coast of Western Australia.

Additionally, most finfish resources in the State are likely to be fully exploited, with only modest scope for expansion. This is based on a long history of commercial fishing, initially with little restrictions or management limits. Despite the long history of commercial fishing, catches have only exceeded 20,000 t.yr⁻¹ in two years since the late 1980s, with catches in the last decade fluctuating between 10,000 t.yr⁻¹ and 15,000 t.yr⁻¹. In addition, recreational effort and catches have only recently been constrained yet catches in the West Coast Bioregion have been not exceeded approximately 300 t.yr⁻¹ despite a population exceeding 1.5 million in the metropolitan area, representing potentially hundreds of thousands of fishers.

Additionally, long-lived species, in low productivity environments result in fishery resources that are highly vulnerably to fishery impacts (e.g. recruitment overfishing, Stephenson & Jackson 2005). If stocks do become over exploited (e.g. Pink snapper in inner Shark Bay; Stephenson & Jackson 2005) recovery periods are in the order of a decade or more (Jackson *et al.* 2010). Initial modelling of over-exploited stocks in the West Coast Bioregion suggest that it may take 10–20 years to rebuild stocks of West Australian dhufish, *Glaucosoma hebraicum* (B. Wise, pers. comm.). A long period of recovery is also likely after non-fishery impacts. For example, in the relatively short-lived species (e.g. pilchards, *Sardinops sagax*, maximum age of nine years (Fletcher & Blight 1996)), stocks in Western Australia are still recovering after the herpes virus of 1998/9 (Gaughan *et al.* 2008), although catches are still below the peak of the mid 1990s.

Due to the high diversity of the finfish species that support fisheries, it is logistically and economically impossible to monitor or assess the status of all species; monitoring must be cost-effective relative to the value of the resource (economic, social and cultural values). To overcome this issue the Department of Fisheries Western Australia has identified species as indicators of the status of a suite of species (DoFWA 2011).

For example, for the inshore demersal finfish resources that support the North Coast Demersal Scalefish Fisheries (Northern Demersal Scalefish Fishery, NDSF, and the Pilbara Demersal Scalefish Fishery, PDSF), more than 100 species of finfish are landed. However, only five species – red emperor (*Lutjanus sebae*, NDSF and PDSF), goldband snapper (*Pristipomoides multidens*, NDSF and PDSF), rankin cod (*Epinephelus multinotatus*, PDSF), blue spotted emperor (*Lethrinus punctulatus*, PDSF) and brownstripe snapper (*Lutjanus vitta*, PDSF) – are currently directly assessed; the status of the these stocks are used to determine the status of the entire suite of inshore demersal fishes that support these fisheries (DoFWA 2011). These species were chosen due to a combination of their vulnerability, based on their life

history characteristics and significance to commercial and recreational sectors (DoFWA 2011).

Similarly, for the 100 or more species that make up the inshore demersal finfish resources that support the West Coast Demersal Scalefish Fishery, only three species – pink snapper (*Pagrus auratus*), the West Australian dhufish (*Glaucosoma hebraicum*) and baldchin groper (*Choerodon rubescens*) – are directly assessed using age structure approaches to determine the status of the entire suite (DoFWA 2011). These three species were chosen due to a combination of their vulnerability, based on their life history characteristics and because both the commercial and recreational fisheries target these species (Wise *et al.* 2007; DoFWA 2011). Indicator species are also monitored for all fisheries in Western Australia (DoFWA 2011). The species monitored are periodically re-evaluated as fishery dynamics and management arrangements evolve.

This information must also be clearly communicated to all stakeholders, not only commercial fishers but recreational fishers and the wider community too. The key messages include;

- Waters of Western Australia are relatively low in terms of productivity
- As a result Finfish stocks, and total catches, will also be relatively small compared to fisheries in many other regions of Australia and the World
- Many of the finfish resources that support fisheries are composed of multiple species
- Many finfish species are long lived (25 + years), especially valuable demersal species
- These characteristics make the finfish resources vulnerable to impacts of fishing and environmental variability.
- If stocks are over-exploited, they will take long periods (in the order of decades) to rebuild under appropriate management arrangements.
- Stakeholder aspirations must be consistent with the potential of the finfish resources and the ecological systems that support them.
- There should also be no illusion that there is room for large-scale developmental fisheries or new fisheries in the order of thousands of tonnes; the waters of Western Australia simply do not support this scale of finfish resources.

Additional challenges for finfish resources in the Kimberley and North Coast Bioregion

The above information also applies to the finfish resources and fisheries in the Kimberley and the North Coast Bioregion. In addition, there are some additional features and challenges for finfish resources in these northern areas of Western Australia.

With the exception of a small extent (~250 km) of coastline east of Cape Londonderry to the Northern Territory border (McGinley 2008d), the entire North Coast Bioregion (including the Kimberley and the Pilbara) is a Class III, low productivity (<150 g.C.m².yr⁻¹) ecosystem (McGinley 2008a). Thus the total fishery productivity of the area is relatively low. While trawling

and other method-based fisheries have been operating in the North Coast Bioregion for decades (Newman *et al.* 2010c), total catches have been relatively modest compared to the extent of the area fished.

Tidal ranges vary along the coastal region of the North Coast Bioregion, but include some of the largest tidal ranges in Australia (e.g. Broome (Kimberley): 10–12 m; Port Hedland (Pilbara): 7 m). These large water movements generate and maintain high levels of turbidity in coastal waters, which limit benthic productivity in marine systems. Coupled with a relatively low rainfall and a low productivity terrestrial system, the total marine productivity of the Bioregion is correspondingly low. This is reflected in the catches of commercial fisheries.

For example, the entire catch of demersal Scalegfish in the North Coast Bioregion from Cape Londonderry to Onslow peaked at approximately 4,000 t.yr⁻¹ and more recent catches are approximately 3,000 t.yr⁻¹ (Fletcher & Santoro 2010). The mackerel fishery that operates throughout the North Coast, Gascoyne and into the West Coast bioregions has a TAC of 410 t.yr⁻¹ of Spanish mackerel plus an additional 180 t.yr⁻¹ of grey mackerel (Molony & Lai 2010).

While similar challenges to other West Australian finfish resources and fisheries, the Kimberley region and entire North Coast Bioregion have additional external challenges, including;

1. An absence of baseline information. The recent Montara oil spill highlighted the lack of baseline information in plankton ecology, oceanography and habitat assessments.
2. The monitoring and assessment of finfish resources in the North Coast is logistically challenging. Many areas are remote and areas north of Broome are virtually only accessible by boat. This makes access difficult and, therefore, any field programs resource intensive.
3. There is an increase in the development of land and maritime-based mining activities. This includes coastal developments (e.g. port facilities) to support iron ore export and oil and gas exploration and exploitation, with wellheads and pipelines being planned and developed across the Kimberley and Pilbara areas. The direct impacts of coastal or maritime development may include the displacement of commercial and recreational access from certain areas and potentially negative impacts from shipping, dredging, spills and other activities associated with these industries.
4. There is expected to be an increase in permanent and transient populations of people in the northern areas of Western Australia, with estimates in the tens of thousands typically located around the existing population centres (e.g. Broome, Port Hedland, Karratha). With more people in the area, there will be more people who will want to undertake recreational fishing activities, with access to fishing highlighted in some of the recruitment advertising. Boat ownership is also likely to be high and this will be verified with the recreational fishing from boats to be surveyed in

2011 by the Department of Fisheries. Thus recreational fishing pressure in the North Coast Bioregion will increase. This may be addressed by the Department of Fisheries Western Australia liaising with the Australian Petroleum Production and Exploration Association (APPEA, www.appea.com.au) to highlight and address the limitations of the productivity in the fisheries and these ecosystems, and the need for sustainable fisheries.

5. The Commonwealth Marine Bioregional Planning strategy being led by the Department of Sustainability, Environment, Water, Populations and Communities (SEWPaC¹) has identified areas in the North Coast that it is considering for inclusion. The spatial management proposed ranges from totally closed areas to general-purpose areas. There will, no doubt, be some closures to areas that are currently open to fishing, which may risk moving existing fishing effort into smaller areas, increasing the risk to sustainability of finfish resources. The alternative is buying out some of this effort although there are few details from the Commonwealth on this option. There is currently only limited ability to restrict recreational effort and catches by the Department of Fisheries.
6. While SEWPaC are putting their Marine Bioregional Planning into effect in waters beyond 3 nautical miles, State Departments, such as the Department of Environment and Conservation (DEC), are also undertaking the planning and establishment of marine parks, which also include areas closed to fishing (e.g. Camden Sound). This will have an additive effect of potentially concentrating existing fishing effort into smaller areas.

Regardless, the existing fisheries themselves are sustainable, albeit with somewhat precautionary limits, and the Department of Fisheries Western Australia will continue to liaise with stakeholders and industry to review current management arrangements and potentially develop alternative objectives, strategies and management arrangements to ensure the sustainability of these fisheries in the long term.

While these fisheries may be relatively modest in an Australian and global sense, making these fisheries deliver high quality products and/or experiences in a sustainable way will ensure the viability of these fisheries into the future.

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¹ SEWPaC is the Australian Government's Department that is responsible for Marine Bioregional Planning in Australia. SEWPaC is in the process of identifying marine areas for different levels of protection, potentially including sanctuary zones. See www.environment.gov.au/coasts/mbp/index.html

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Use of historic fisheries data to determine trends in relative abundance and body size of sailfish, *Istiophorus platypterus*, off northwestern Australia

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Abstract

Sailfish (*Istiophorus platypterus*) appear annually off northwestern Australia in large numbers, supporting substantial recreational and charter fisheries in which almost all fish are released. The main centres for this activity are the towns of Broome, Dampier and Exmouth. Examination of historic Japanese longline catch data from northwestern Australia indicated that relatively few sailfish were caught off this area between 1979 and 1998, although little fishing effort occurred during the peak sailfish 'season'. Long term recreational fishery data, consisting of tag and release and charter boat diary data, were used to investigate locations of captures, seasonality of the sailfish aggregations and trends in body size and relative abundance of sailfish through time. No trends in annual catch rates were discernible from the mid 1990s to the present. Sailfish may be caught in most months off Broome, with the average peak period being June through September. Sailfish caught off Broome, as determined from estimated weights at tag-and-release, are slightly, but significantly smaller than those caught off Dampier while fish caught near the Rowley Shoals, and in the Exmouth Gulf, are larger than those caught off Broome and Dampier.

Keywords: Sailfish, *Istiophorus platypterus*, northwestern Australia, recreational fisheries

Introduction

The sailfish, *Istiophorus platypterus* (Shaw & Nodder 1792) is a member of the billfish family Istiophoridae, which also includes the marlins and the spearfishes, all of which are high trophic level predators. Sailfish occupy tropical, subtropical, and occasionally temperate waters throughout the Indian, Pacific and Atlantic Oceans (Nakamura 1985), mostly between 30°N and 30°S, with poleward expansions of range during summer months in both hemispheres (Beardsley *et al.* 1975). Recent taxonomic and phylogenetic research on billfishes, based on molecular genetics, supports the existence of a single circumglobal species of sailfish, *Istiophorus platypterus* (Collette *et al.* 2006).

Sailfish, unlike most species of billfish, commonly aggregate in relatively shallow nutrient-rich neritic waters (<150 m depths). Known areas of high seasonal concentration of sailfish include the Pacific coast of central America, including Mexico, the Gulf of Mexico, especially the coast of Florida, the Malaysian peninsula, several grounds inside the Great Barrier Reef, and off the northwestern Australian coast, especially in the region of Dampier and Broome.

Because of these seasonal aggregations of sailfish in coastal areas, a recreational fishery developed in the 1960s (Howard & Stark 1975) and 1970s in northwestern Australia that primarily targets sailfish. Dampier and Broome are now the main centres for this activity but significant numbers of sailfish are also caught off Exmouth. In all three areas, virtually all of sailfish caught are either tagged and released, or released. These fisheries are reputed to generate considerable economic benefits for the region. Very little is known, however, about the biology of sailfish in the region, especially in regard to the species' spatial and temporal distribution and movement patterns. Therefore, a study was undertaken to collate and analyse historic fishery data relevant to sailfish in the region with the aim of determining catch rates through time, size distribution of the catch and seasonality of the appearance of sailfish in these areas.

Methods

Data were derived from a range of sources. Commercial Japanese longline catch and effort statistics were derived from Campbell *et al.* 1998. Information on the Taiwanese gillnet fishery was also derived from Campbell *et al.* 1998, and Stevens & Davenport 1991. For

the recreational fishery, raw data on sailfish tagged between 1979 and 2009 were obtained under a data licence agreement from Industry & Investment NSW (Fisheries). Tagging data includes the following details for each fish tagged and released: Tag number, species, date, location, estimated size (weight and/or length) at release, boat and angler name.

Median weight estimates were compared using a one-way ANOVA on Ranks and post-hoc comparisons following Dunn's Method.

Catch and effort data for the annual Broome Sailfishing tournament were kindly extracted and supplied by the Broome Fishing Club for the period 1997 to 2009. These data were extracted from radio reports. At 10:00 am, 1:00 pm and 4:00 pm on each fishing day, each boat is contacted and asked to give a fishing report. Such reports record the position of the boat, and how many sailfish (or marlin) the boat has raised, struck, hooked and/or released in the previous period ('raised' means a sailfish or marlin observed following a bait or lure; 'struck' means a sailfish or marlin that attacks a lure or bait, but fails to become hooked). These data are consistent over the history of the data set (1997 to 2009) and provide some measure of catch per unit of effort (CPUE), and therefore relative abundance of fish, through time.

For the purposes of this study, two charter boat operators who have actively fished for sailfish off Broome over lengthy periods kindly provided their personal records of sailfish catches over time. These data recorded the number of days fished each year, and the number of sailfish caught (released, or tagged and released) on each

day fished. (Note that these data are separate from compulsory logbook catch records required to be submitted to the Western Australian Fisheries Department by all charter operators since 2004).

Logbook charter data was obtained from WA Fisheries. It is important to note that due to confidentiality arrangements, sailfish release data are not included if there were less than three charter boats operating in any given statistical grid during the period under consideration.

Results

Historic commercial fisheries

Japanese longlining commenced off northwestern Australia in the 1950s, primarily targeting southern bluefin tuna, *Thunnus mccoyi*. While the targeting of southern bluefin tuna was halted in the region in the early 1970s, longlining in the region, mainly for yellowfin tuna, continued until 1997/98 when Japanese vessels were excluded from the 200 nm Australian Fishing Zone (AFZ). Previously, waters within 50 nm of Exmouth were closed to Japanese longlining in 1990/91 extending to a closure of all waters within 50 nm of Western Australia north of 35°S in 1992/93. At the same time, in areas beyond 50 nm, billfish other than broadbill swordfish were not to be deliberately targeted (Campbell *et al.* 1998).

Table 1 shows the reported annual catch of billfish (numbers) by Japanese bilateral and joint venture

Table 1

Fishing effort (number of hooks) and catches (number) of billfish caught by Japanese bilateral and joint venture longline vessels operating within the AFZ west of 125°E since 1979. BAM = black marlin, BUM = blue marlin, STM = striped marlin, SLF = sailfish, BBL = broadbill swordfish.

Year	Hooks	BAM	BUM	STM	SLF	BBL
1979	58,100	12	13	98	0	40
1980	769,804	241	127	625	0	727
1981	1,664,220	394	223	777	48	1,037
1982	1,069,224	550	314	622	20	600
1983	1,288,795	450	112	1,060	35	642
1984	2,803,353	2,256	1,027	6,299	203	1,250
1985	2,490,880	2,167	785	3,500	101	1,711
1986	2,798,925	1,166	710	934	160	1,200
1987	4,389,658	814	290	1,043	218	1,685
1988	957,716	603	365	232	173	416
1989	711,880	362	216	108	184	353
1990	1,223,450	291	301	103	29	711
1991	167,232	0	3	0	1	696
1992	533,024	0	0	3	0	308
1993	3,257,023	21	6	40	33	2,575
1994	2,495,635	250	246	143	45	1,419
1995	2,494,203	320	476	160	78	1,204
1996	756,135	4	18	51	5	1,754
1997	161,400	36	19	10	34	43

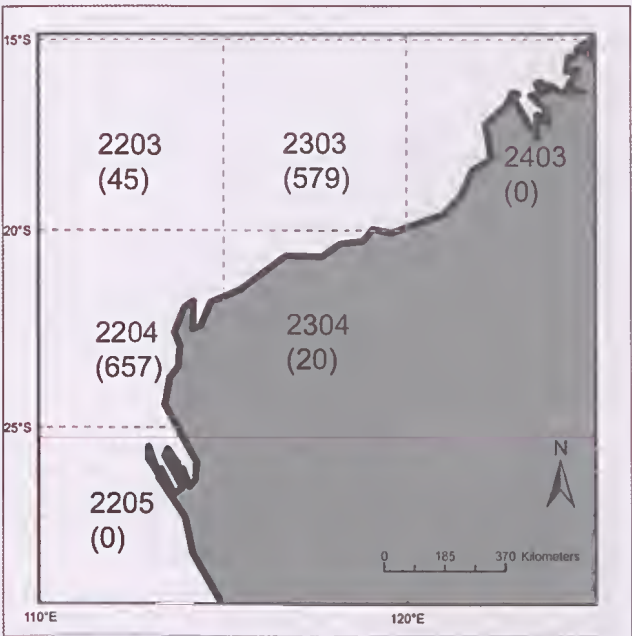


Figure 1. Numbers of sailfish & spearfish caught (in brackets) in 5° statistical areas off northwestern Australia by Japanese longline vessels between 1979 and 1998.

longline vessels operating within the AFZ west of 125°E since 1979 (from Campbell *et al.* 1998).

Between 1979 and 1997, compared with other istiophorids (black, blue and striped marlin), very few sailfish appear in catch records of Japanese longline vessels fishing in Western Australian waters. Several aspects of recording sailfish catches are important to note in this regard. Sailfish and shortbill spearfish (*Tetrapturus angustirostris*) were combined in Japanese logbooks, so the actual catch of sailfish recorded would be less than

indicated. However, spearfish are uncommon in this region, so it is likely that the figures given for sailfish/spearfish in this instance do represent primarily sailfish. It is also noted that sailfish were not regarded as a desirable species to retain by Japanese longliners so it is likely that many were discarded at sea without being recorded.

Figure 1 shows areas where sailfish were historically recorded by Japanese longliners. No sailfish were recorded adjacent to Broome (grid 2403) and only a small number were recorded adjacent to Dampier (grid 2304). The largest numbers of sailfish were taken immediately adjacent to these areas (grid 2303) and in the grid adjacent to Exmouth Gulf (grid 2204).

The low catches of sailfish in areas where the species is caught in large numbers by the recreational fishery can be largely explained by the fact that Japanese longlining only took place at or beyond the boundary of the continental shelf, in waters normally deeper than 200 m (Campbell *et al.* 1998). This boundary is well outside the area where sailfish have been, and are targeted by the recreational fisheries off Broome and Dampier, but much closer to the sailfish grounds off the Exmouth Gulf (Fig. 2).

More importantly though, Japanese longline effort was historically almost entirely absent from northwestern Australia during the months of April to September, the peak period of encounter with sailfish by the recreational fishery off both Broome and Dampier (Fig. 3 and Fig. 9).

A large-scale Taiwanese gillnet fishery that targeted *Carcharhinid* sharks operated off northern Australia from 1972 to 1986. Before the declaration of the 200 mile Australian Fishing Zone in 1979, this fishery was active to within 12 nautical miles of the coast, and while the great majority of fishing effort was expended to the north of Arnhem Land, Northern Territory, a small amount of effort extended to the waters off the coast, just to the north of Broome (Stevens & Davenport 1991).

Australian observers monitored this fishery from 1984 and results indicated a significant bycatch of sailfish and juvenile black marlin throughout the region, averaging

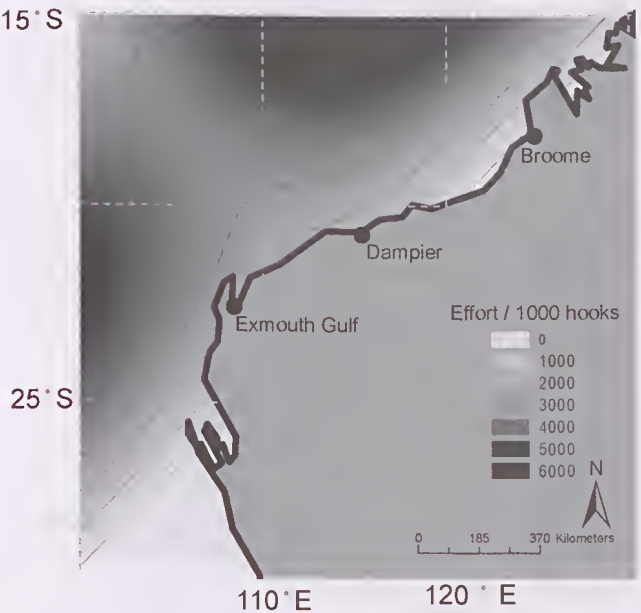


Figure 2. Contours representing number of hooks set by Japanese longline vessels off northwestern Australia between 1979 and 1998. Note that the fishing effort near Broome and Dampier was extremely low.

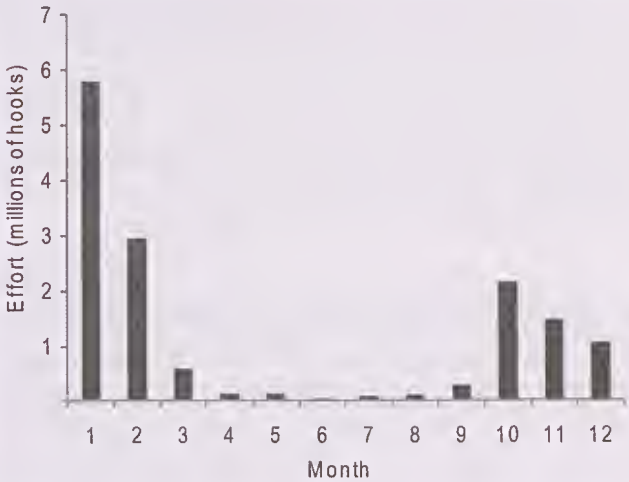


Figure 3. Cumulative effort (millions of hooks) by month of Japanese longline vessels off the coast of northwestern Australia (15–30°S; 110–125°E) between 1979 and 1998. A total of 14,510,849 hooks were set.

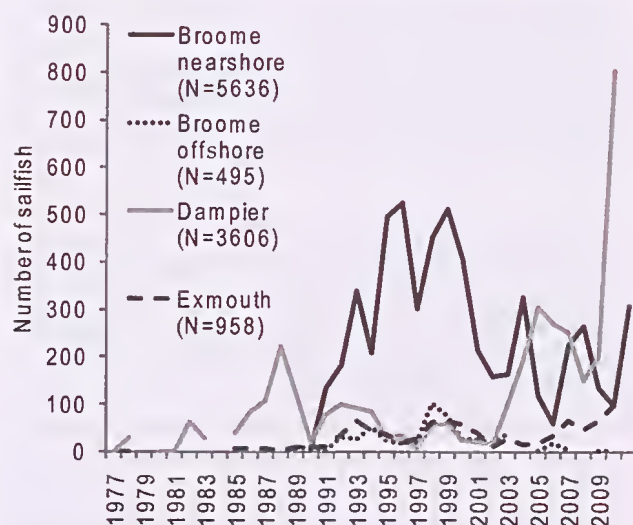


Figure 4. Total number of sailfish tagged by recreational anglers each year off four main regions of Western Australia.

one billfish per gillnet haul. Analysis suggested that the catch would have been of the order of 6 black marlin and 5 sailfish per 1000 km/hour of fishing effort (Campbell *et al.* 1998) which would convert to tens of thousands of both species of billfish over the life of the fishery. Campbell *et al.* (1998) caution against the use of these estimates but do state that the fishery was "probably a substantial source of billfish mortality" at the time. However, given the very small amount of fishing effort off Broome, and none further south, the catch of sailfish in the study area could only have been a small fraction of the total catch.

Recreational fishery for sailfish off northwestern Australia

The total catches of sailfish by recreational anglers off northwestern Australia are unknown. However, details of all sailfish tagged by anglers in the region since the 1970s are held by NSW Industry & Investment's Australian Gamefish Tagging database (Pepperell 2009). As of June 2009, the total number of sailfish tagged off Western Australia since 1978 was just over 11,190. Of these, 10,695 had been tagged off the northwest coast. Figure 4 shows the annual number of sailfish tagged in the waters off the three major centres of interest – Broome, Dampier and Exmouth, together with numbers of sailfish tagged wide of Broome (termed 'Broome offshore'), which is the region primarily around the Rowley Shoals, about 175 nm ENE of Broome).

Sailfish tagging in Western Australia commenced off Dampier in 1978, with numbers tagged generally being less than 100 fish year until the early 2000s when numbers tagged increased substantially to a peak of over 800 fish in 2009 – the highest recorded for any region off Western Australia. A total of 3,606 sailfish had been tagged off Dampier by the end of 2009.

Sailfish tagging off Broome commenced in 1988 with numbers tagged rapidly increasing to annual totals of around 500 fish in the mid 1990s. Numbers tagged then declined, fluctuating between about 100 and 300 fish in the 2000s. A total of 5,636 sailfish had been tagged off Broome by the end of 2009, more than any other area in Western Australia.

Catches off Exmouth have been low in comparison, with peaks of more than 50 fish tagged in some years, increasing consistently over the past several years. A total of 958 sailfish had been tagged off Exmouth by the end of 2009, most of these inside Exmouth Gulf.

Offshore sailfish taggings have been somewhat intermittent, presumably because of the remoteness of the Rowley Shoals. Nevertheless, nearly 500 fish had been tagged in offshore areas by the end of 2009, with most activity in the mid 1990s.

Sizes composition of the recreational catch

When a sailfish is tagged and released, an estimate of the size of the fish is nearly always recorded by the angler on the tag card. These estimates are generally agreed upon by all present on the boat, and while length estimates are sometimes included, the overwhelming majority of estimates are given as weights (kg).

Figure 5 shows the size distribution of all sailfish tagged off the four areas for all fish where weights were estimated. This suggests difference in sizes of sailfish tagged in different areas. Indeed, significant differences were found (Dunn's, $P < 0.05$) in the mean estimated weights of sailfish tagged between all regions investigated, except between Broome offshore and Exmouth (Fig. 6). The mean size of fish is smallest off Broome, followed by those caught off Dampier, Exmouth and Broome offshore.

When mean weights of sailfish are disaggregated by quarter, a possible seasonal trend in increasing size of fish off both Broome and Dampier is seen, at least from the second to the fourth quarter (Table 2). This could indicate that fish are remaining on these grounds and growing in average size through the season.

Table 2

Average weights (estimated) of sailfish tagged-and-released throughout the study area.

Quarter	Broome nearshore			Broome offshore			Dampier			Exmouth		
	N	Mean	StdDev	N	Mean	StdDev	N	Mean	StdDev	N	Mean	StdDev
1	9	19.67	8.69	2	28.50	9.19	136	20.23	10.00	190	30.24	12.31
2	514	19.22	6.83	47	26.02	7.88	1068	19.11	9.21	74	32.80	11.19
3	4937	19.87	7.21	356	28.63	9.38	2211	22.45	7.18	199	30.69	9.60
4	176	21.03	6.28	90	31.39	9.43	191	22.78	8.19	495	25.68	10.16
Total	5636	19.85	7.16	495	28.88	9.34	3606	21.39	8.15	958	28.18	10.90

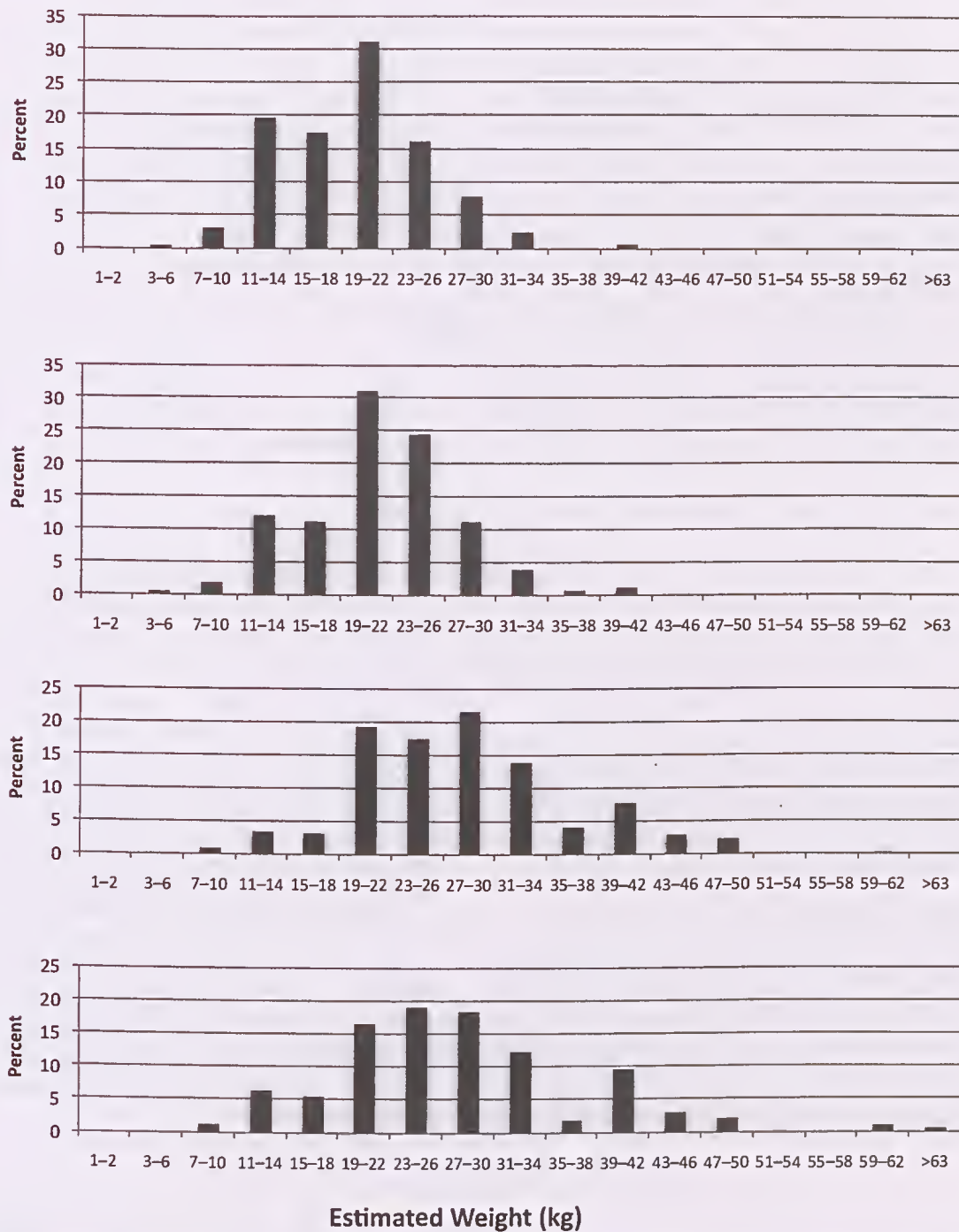


Figure 5. Size distributions (estimated weights of tagged fish) of sailfish tagged and released in the four main recreational fishing areas off Western Australia since 1989.

The Broome recreational sailfish fishery

Several data sets are available from the Broome area that are not available for the other recreational sailfishing areas in Western Australia. These include detailed records of all sailfish interactions (raised, struck, hooked and released) during the annual Broome Sailfishing Tournament, numbers of boats fishing each tournament day from 1997 to 2009, WA Fisheries records of charter boat catches of sailfish in the area 2004 to 2007 (see caveats below), and personal diary records of sailfish catches by two sailfish specialist charter captains from 1996 to 2009.

Catches through time

The rates (fish per boat day) of sailfish raised, struck, hooked and tagged during the annual Broome Sailfishing Tournament for 1997–2009 are shown in Figure 7. The numbers of fish raised per boat day are obviously the highest among these measures, but while this figure theoretically provides an index of abundance, in reality the same fish may be raised again and again by the same or different boats. Therefore, the hookup and release (tag) rates are considered to be better indicators of relative abundance.

Comparison (ANOVA on Ranks; Dunn's)	Q	P <0.05
Exmouth vs Broome inshore	26.7	Yes
Broome offsh vs Broome inshore	22.8	Yes
Exmouth vs Dampier	16.6	Yes
Broome offshore vs Dampier	15.3	Yes
Dampier vs Broome inshore	15.3	Yes
Broome offshore vs Exmouth	2.3	No

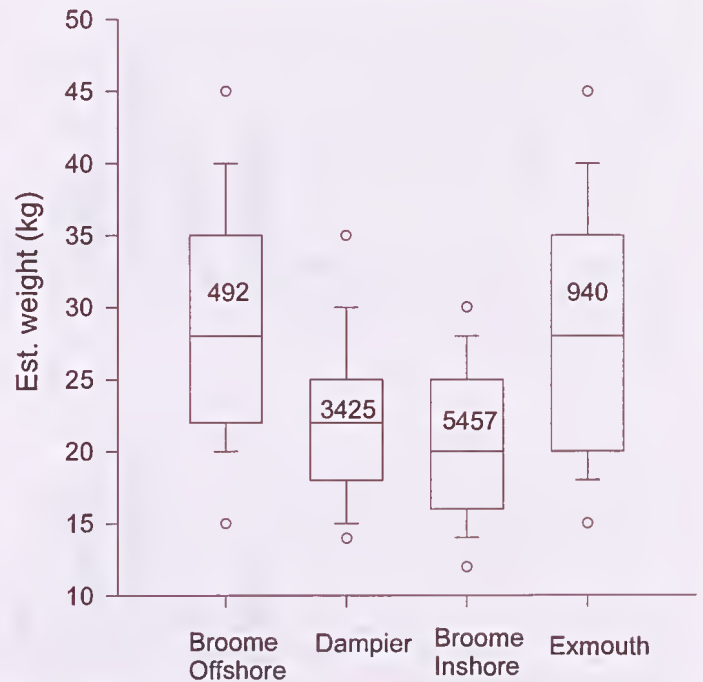


Figure 6. Median estimated weight of sailfish tagged-and-released at different locations off the coast of northwestern Australia between 1977 and 2009. N = sample size. Middle line represents the median and ends of boxes define the 25th and 75th percentiles. Error bars at 10th and 90th percentiles and 5th and 95th percentiles are represented by open circles.

There was no clear temporal trend in the rates of hook-ups and fish tagged per boat day. The highest number of fish interactions occurred in 2002 followed by two poor years, and then fairly consistent annual catches occurred thereafter.

Catch rates by charter boats

The two sets of personal records from the cooperating charter operators begin in the 1990s and as such, are valuable independent sources of information on catch rates through time. Also, because charter boats fish over a much greater part of the year than a given fishing tournament, their records are very useful in determining the seasonality of sailfish in the area. It is also important to note that while the charter operators

do tag sailfish at certain times, most notably during tournaments, they do not necessarily do so at other times, but may simply release sailfish without tags. These are still recorded by the operators, resulting in their records of released fish being somewhat, but not entirely separate from release information recorded on tag cards. Regarding the representativeness of the data from these operators, examination of total sailfish releases shows that, for the years where mandatory logbook data were available (2004–2007), charter operator 1 accounted for 66.3% of all sailfish caught and released off Broome by all charter operators. It is further recognized that during the mid to late 1990s, operator 2 was by far the most active and successful sailfishing charterer in the region.

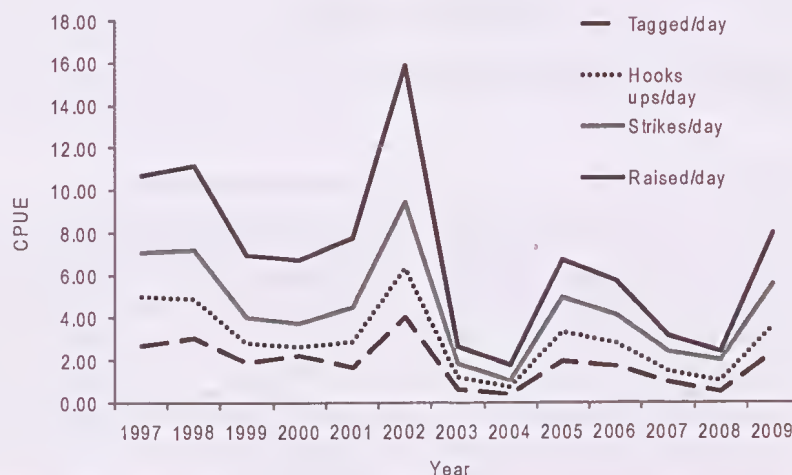


Figure 7. Numbers of sailfish raised, struck, hooked and tagged per day in the Broome Sailfishing Tournament, 1997–2009.

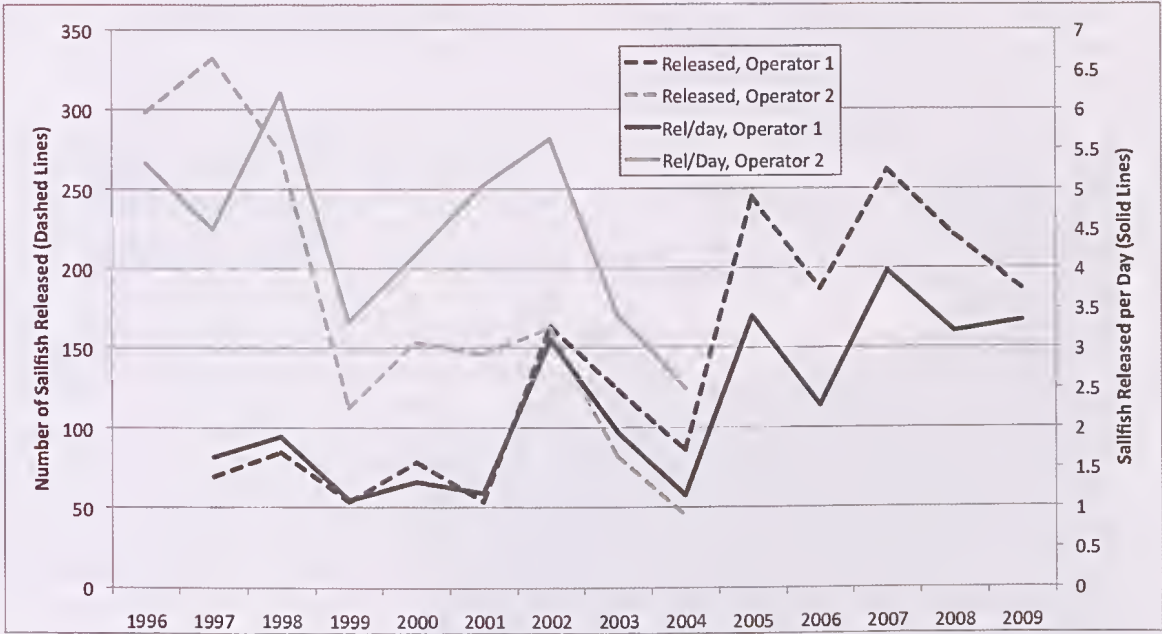


Figure 8. Catch and catch rate of sailfish by charter operators 1 and 2.

Figure 8 shows numbers of sailfish released each year and the annual catch rate (numbers released per day fished) by both charter operators (with the caveat that, for operator 2, the total number of days fished are unknown and therefore 'effort' is defined as the days on which at least one sailfish was released). For operator 1, there is a general trend of an increase in catch and catch rate through time while for operator 2, there is a downward trend in catch and catch rate to the end of the series (2004). This trend in catch rate is primarily due to the fact that the vessel was not necessarily targeting sailfish consistently in the last three years of the series, as indicated to the authors by the operator.

Seasonality of sailfish off Broome

The seasonality of the appearance of sailfish off Broome can be considered by examining the catches of charter operator 2, who recorded catches (releases) of sailfish by month during the years of operation off Broome. Figure 9 shows the numbers of sailfish released by month for selected years together with the totals summed for each month between 1996 to 2004.

This shows that, while at least some sailfish may be caught in every month of the year, there is a clear seasonality in the availability of sailfish off Broome, with the main months through this time series being June

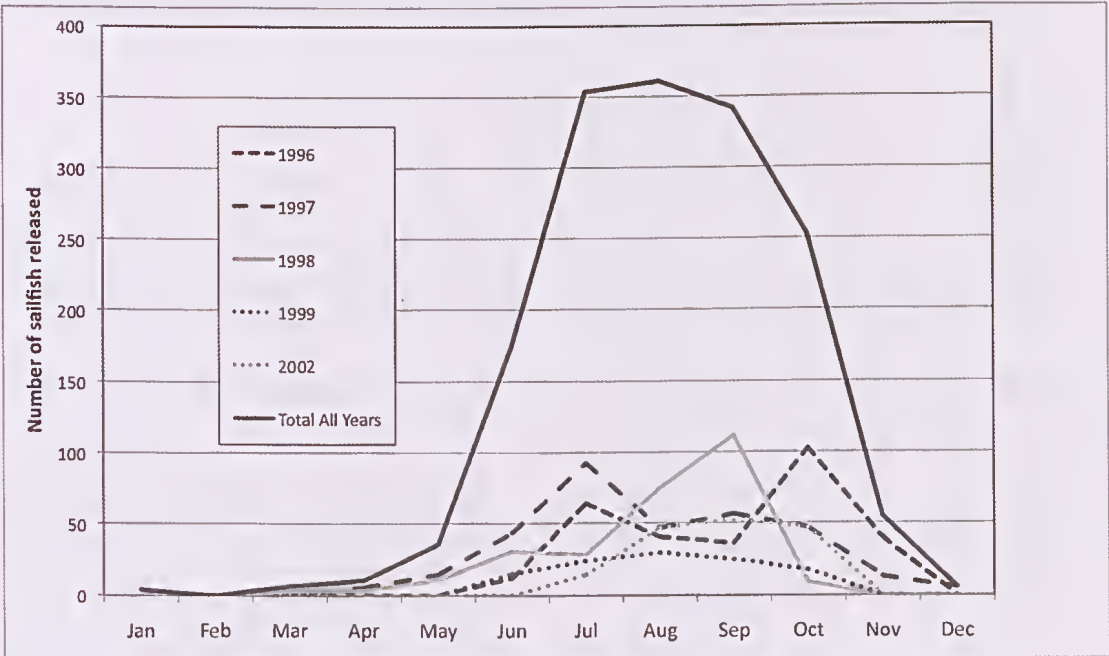


Figure 9. Releases of sailfish by month by charter operator 2. For purposes of clarity, not all years are shown

through October and the peak months being July through September. Interestingly, the three highest catches over this time period were recorded in separate months – July 1997, September 1998 and October 1996. It might be argued that catches are highest during this period because this is when fishing is mainly conducted. However, pelagic gamefishing is conducted from Broome in every month of the year, so the timing of the appearance, peaking and disappearance of sailfish from the area, as indicated in Figure 9, is considered to be a real.

Size distribution of sailfish off Broome

As noted above, the estimated size of sailfish caught off Broome (derived from tag cards) is significantly smaller than the other areas considered. Considering now the sizes of sailfish caught off Broome through time, Table 3 presents the weight frequency of all fish tagged off Broome from 1989 to 2009. This shows that the size range and modal size of sailfish released off Broome have been remarkably consistent for over 20 years. The majority of fish (87.2%) have been estimated to weigh between 11 and 25 kg even though the modes within this range vary slightly between years.

It is noteworthy that very small sailfish (1 to 5 kg) have been caught (released) off Broome in a number of years, most notably, in 1996, 2001, 2002, 2005, 2006 and 2009. At this size, these fish would only be several months old (Hoolihan 2006) and could indicate good recruitment years to the population. However, there does not appear to be any obvious relationship between those years when very small fish appeared and subsequent high catches of larger fish in succeeding years as this cohort moved through the fishery. Even so, a more in-depth analysis of this would be warranted since it could

provide some predictability regarding the fishery in years to come.

Catches by location

The accuracy of locations given for releases of tagged sailfish recorded on tag cards is inconsistent, with many anglers simply recording a general area of their catch (such as 'Broome', 'Dampier' or 'Exmouth'). However, a substantial number of records do give locations, each of which has been converted to co-ordinates on the New South Wales I&I tagging program database. Figure 10 shows density plots of numbers of sailfish tagged off northwestern Australia by half-degree grids for the entire tagging database (1979 to 2009). Figure 10 also shows the grounds fished by the recreational fishing communities of the three primary recreational sailfishing areas, Broome, Dampier and Exmouth. It shows that sailfish were tagged near each of these ports, which is not surprising since those are the centres of fishing activity. However, this also shows that in each case, fish are tagged in greater numbers in a small number of half-degree grids.

These data do not allow particularly fine scale inspection of the locations of catches of sailfish. However, one set of data did allow this kind of treatment – charter log data as provided to the Western Australia Fisheries Department. These data are summarised for the Broome region for the years 2004 to 2007 in Figure 11. It is important to note that due to confidentiality arrangements, sailfish release data are not included if there were less than three charter boats operating in any given grid. This Figure shows density plots of numbers of sailfish released within 10 nautical mile grids between March and November, combined for the four years for which data were available. As is the case for the personal

Table 3

Numbers of sailfish in each estimated weight category tagged each year off Broome, WA

Wt (kg)	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
1-5	0	0	0	0	0	1	0	3	18	5	0
6-10	0	2	4	11	4	16	14	10	18	36	9
11-15	0	17	30	44	42	74	113	105	79	101	57
16-20	3	54	75	105	80	182	247	120	189	153	133
21-25	2	41	45	104	60	167	105	56	90	121	136
26-30	1	15	22	62	16	43	30	8	43	61	45
31-35	0	3	3	8	6	11	8	0	10	23	17
36-40	0	1	1	3	2	1	4	1	5	4	8
41-45	0	1	0	1	0	0	1	0	0	0	0
>45	0	0	3	0	0	1	2	0	0	7	0
Total	6	134	186	338	210	497	526	303	452	518	405

Wt (kg)	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Total
1-5	0	0	21	29	1	2	44	18	5	5	33	185
6-10	3	1	1	0	2	0	15	8	4	3	2	163
11-15	18	27	31	27	32	13	98	55	64	33	53	1113
16-20	55	77	47	134	58	33	46	120	40	28	103	2082
21-25	88	39	40	93	19	11	12	49	14	16	64	1372
26-30	37	11	9	22	6	1	5	13	7	9	34	500
31-35	8	2	11	11	0	0	3	1	0	3	14	142
36-40	4	1	4	4	1	0	2	1	0	1	4	52
41-45	1	1	1	3	0	0	1	0	0	0	0	10
>45	0	0	0	3	0	0	0	0	0	0	1	17
Total	214	159	165	329	119	60	226	265	134	98	309	5636

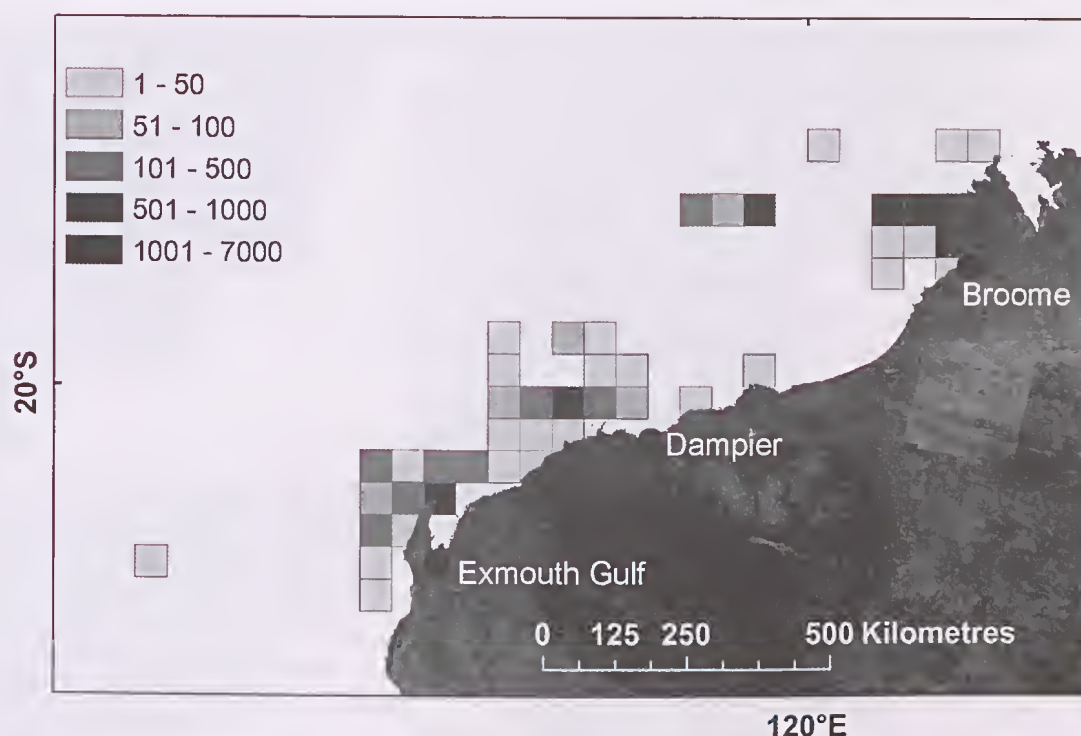


Figure 10. Distribution of recreational catch (taggings) of sailfish off northwestern Australia, 1979 to 2009. Shading of grids indicates numbers of fish tagged.

charter data, this shows that the main fishing seasons are winter and spring, with some variations in highest catches of sailfish between those two seasons. It is also clear that very few sailfish are caught by charter boats in Autumn, although it is likely that fishing effort is low at that time. There is a suggestion from inspecting these charts that more fish are caught in the northern parts of the main fishing grounds later in the fishing season (winter to spring). Combining data for all seasons shows that by far the greatest number of sailfish have been released in just four of the 15 grids where sailfish were caught.

Discussion

Of the five istiophorid species that occur off northwestern Australia, the sailfish is caught (released) in by far the highest numbers by the recreational fisheries of the region. The fishery is perceived to be important for the economies of Broome, Dampier and Exmouth, but until now, there has been no analysis of pertinent historic information on the relative abundance of sailfish in the region.

Historic Commercial Data

Japanese longline fishing was active off the Western Australian coast from 1979 to 1997. The main area where sailfish were caught was between 15° and 25°S and 110° to 120°E, an area encompassing the three recreationally important sailfishing centres of Broome, Dampier and Exmouth. However, few sailfish were taken off these areas, because of both the offshore nature of the fishery and the lack of fishing effort during what we now know to be the peak sailfishing season. A Taiwanese gillnet

shark fishery that operated off northern Australia from 1972 to 1986 most likely caught tens of thousands of sailfish, but again, fishing effort off Broome and the other centres to the south was very small.

The true size of the historic commercial sailfish catch in the region is difficult to determine because of possible underreporting, however, the impact of historic commercial fishing on sailfish in the region is considered to be light.

Recreational catches and catch rates

Three sources of recreational fishery data examined to consider catches and catch rates of sailfish off Broome through time. (Broome was the only area from which these three data sets were available) were gamefish tagging data on released fish, radio reporting data from the annual Broome Sailfish Tournament and personal charter records of long term operators in the Broome area (1996 to present). These data may not be representative of the entire recreational fishery that may catch sailfish off northwestern Australia, but because of their consistency, provide valuable information on relative abundance and body size of sailfish through time. Two broad scale surveys of recreational fishing failed to detect sailfish in the catch in sufficient numbers to provide any estimates of total catch (Henry & Lyle 2003; Williamson *et al.* 2006) and this, together with the experience of the authors suggests that recreational catches of sailfish outside the data sets examined are small in comparison.

Catches of sailfish off Broome, as indicated by tag-and-release data (Fig. 4) have fluctuated considerably on an annual basis. The two major peaks were in 1992/1993 and in 1996/1997 (ie, two major years in succession in each case). It needs to be borne in mind that the tag data,

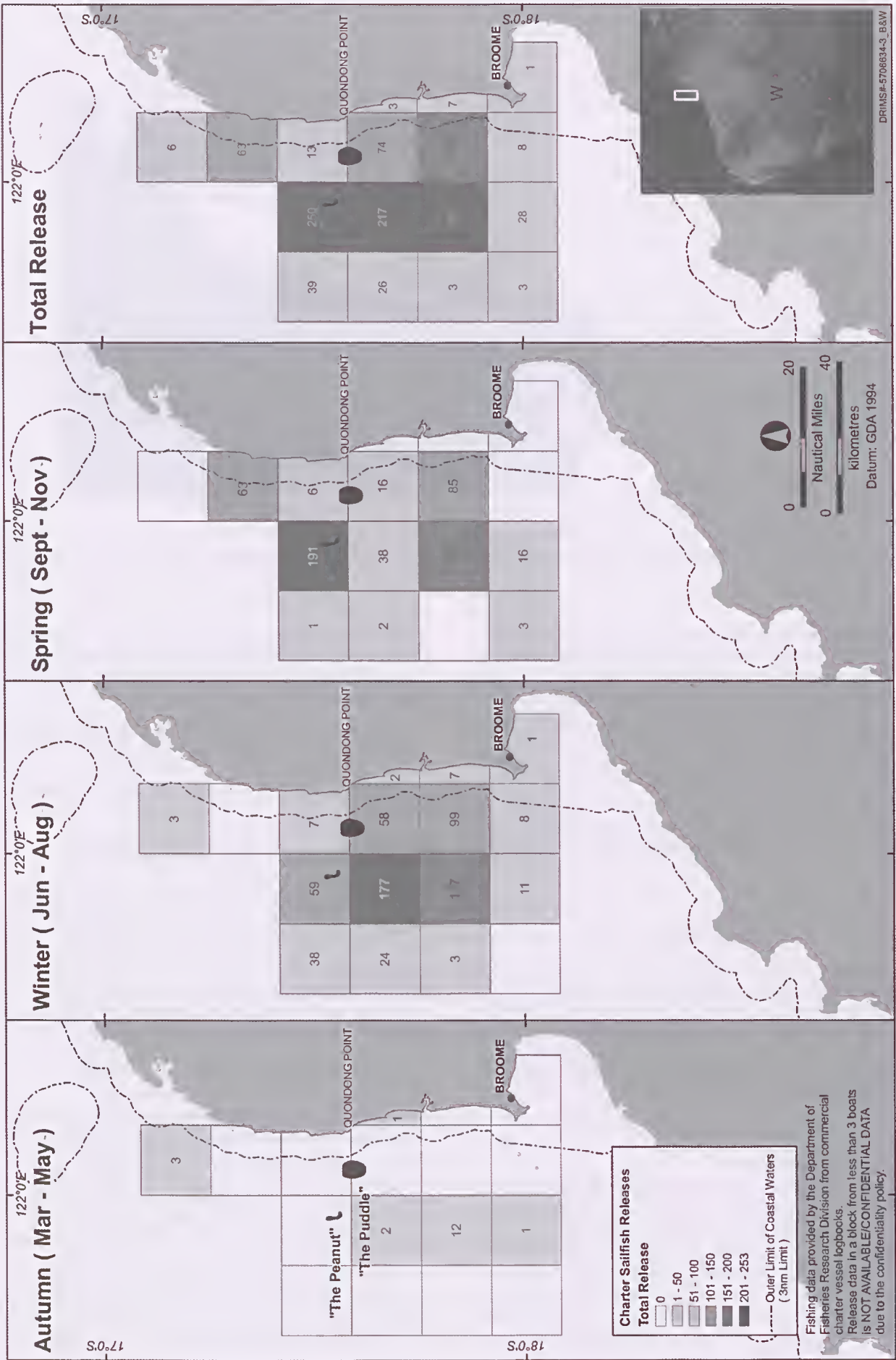


Figure 11. Catches (releases) of sailfish by Western Australian charter vessels, 2004 to 2007. Numbers of fish released are shown in each grid.

while dominated by the annual tournament which takes place over only one week, also would include any fish tagged outside that period, either by private boats or by charter vessels. When considering relative abundance of fish, tournament radio reporting data has the advantage of including effort data, so that catch rates (a surrogate for abundance) can be determined. Tournament data (Fig. 7) also show marked fluctuations of catch rates from year to year, although these are dampened somewhat if only hookup and release rates are considered. (These two measures are also thought to be better indices of abundance than fish raised or struck). Considering these data, there does not appear to be any trend in declining or increasing catch rates through time.

Catch rates of two long-term Broome charter operators examined to analyse catch rates extending well outside the peak tournament period also showed marked fluctuations through time, with similar timing of peaks and troughs during the overlapping periods of both operators. This suggests that their catch rates were indicative of relative abundance of fish through time. After 2004 there has been a consistent increase in catch and catch rate for the charter operator covering this period. This is also reflected to some extent in the tournament catch rates for the same period although 2007 is a good example of a year when tournament catch rate was relatively low, but the charter catch rate was high. This latter result shows the importance of collecting catch and effort data throughout a season.

The data from the charter operators were also valuable in considering the seasonality of the appearance of sailfish off Broome. It was clear from these data that, while sailfish were caught in most months throughout the time series considered, there was a peak season of abundance of fish between July and September inclusive, in some years extending into October.

Size of fish through time

The examination of sizes of fish caught through time can provide insights into such factors as impacts of fishing or growth rates over short and long terms. Sizes of fish from tag records do present some problems since they are only ever estimated by anglers, in most cases, an estimated weight. These estimates are agreed upon by crew members on the tagging vessel, but since fish are rarely weighed (virtually never off Broome), some doubts about the absolute validity of these estimates are sometimes raised. Nevertheless, it has been shown in other studies (primarily by examining actual weights of recaptured billfish against estimated weights at release) that angler estimates can be quite accurate. For example, tag-and-release weight estimates for striped marlin caught on the east coast of Australia and New Zealand match within 8% of the mean annual weight measured by certified scales (Kopf 2010).

The distribution of estimated weights of sailfish released in each of four regions (Fig. 5) indicates some overall differences in average sizes among regions through time. This translates as statistically significant differences in median sizes of fish among all four regions, other than between Exmouth and Broome offshore, as shown in Figure 6. When the size frequencies of fish tagged off Broome are examined (Table 3), it is clear that

the size range of sailfish caught in the region is remarkably consistent through time.

The lumped mean estimated size data also suggest a general increase in size of fish through the year (second to fourth quarter) for both Broome and Dampier. This suggests that, at least in both of these areas, a cohort of sailfish may tend to stay in the general region for a number of months, growing noticeably during this time. Of course, this kind of residence would need to be determined on a year by year basis, ideally by electronic tagging, but it does lend weight to the notion that sailfish generally do not move very far *en masse*.

Prime catch areas

Charter boat logbook data, as supplied by Western Australia Fisheries (not including block data where less than three charter boats had supplied data), clearly show the areas where the majority of sailfish have been caught and released by the charter component of the Broome fishery. These prime sailfish grounds cover an area of about 30 to 40 nm², and include in the highest catch area a bottom feature known colloquially by recreational fishers as 'the peanut'. Another feature known as 'the puddle' does not appear to show consistently as high catches as adjacent grids to the west (Fig. 12).

Although the recreational tag data do not provide as well-defined locations of catches as do the charter data, they are spread over a much longer period, and also indicate the same general area as the region of highest catches through time (Fig. 11).

While no specific studies of sailfish (or other billfish species) in the region have been undertaken in the past, the collation of existing data on catches (releases) and fish sizes from a range of sources has enabled the gleaning of some important insights into the fisheries extending back to their origins. The recreational fishery off the areas of interest, especially off Broome, has proven to be consistent through time with respect to both catch rates and size distribution of the catch. Some evidence suggests that sailfish may have residence times of at least several months in the different regions considered, although there is also clear evidence of seasonality in appearance of fish in large numbers which also suggests movement to and from these areas on a regular basis.

Future studies of sailfish in the region could address a number of gaps. These include estimates of the total catches of sailfish and other pelagic species, analysis of the relative abundance of sailfish off northwestern Australia with respect to historic environmental cues, investigations of the short and long term movements of sailfish, and studies of growth rates and reproduction of sailfish across the region.

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North-western Australia as a hotspot for endangered elasmobranchs with particular reference to sawfishes and the Northern River Shark

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Abstract

Recent targeted surveys, together with the collection of sawfish (Pristidae) rostra from the general public, have demonstrated that the Kimberley and northern Pilbara are important refuges for sawfish, with four of the world's seven species found here. These comprise all of Australia's known sawfish species, including the three species protected under the *Environment Protection and Biodiversity Conservation (EPBC) Act 1999*, i.e. Freshwater Sawfish (*Pristis microdon*), Dwarf Sawfish (*Pristis clavata*) and Green Sawfish (*Pristis zijsron*). The Northern River Shark (*Glyphis garricki*), which was only described in 2008, has only recently been discovered in the Kimberley and is listed as *Endangered* under the EPBC Act. These species are listed as *Critically Endangered* on the IUCN Red List and collectively represent ~45% of Australia's elasmobranchs that are listed as *Vulnerable* or higher under the EPBC Act. There is, however, limited information on the spatial extent of these species throughout Western Australia, particularly as most sawfish surveys have targeted only a few specific areas over a vast coastline. We therefore encouraged public participation in providing *Pristis* rostra, taken from the fish as curios, in order to extend the known locations of the species and relate these to life history stages based on their size. Here we report on the published records and our unpublished catches ($n = 376$) across three *Pristis* spp., and collate this with data from donated rostra, 73% ($n = 283$) of which were considered usable, in that catch locations were reliable and they were from Western Australian waters. We provide information on sawfish distributions in Western Australia and identify areas that are important as pupping grounds, nursery areas or harbour mature individuals. We also collate known records of *G. garricki* and provide information on the ecology of this and the EPBC listed sawfish species.

Keywords: Pristids; *Pristis*; Kimberley; *Glyphis*; Western Australia

Introduction

There are currently 10 species of elasmobranchs that are listed under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) in Australian waters. These include one species that is *Critically Endangered*, two species that are listed as *Endangered*, six species that are listed as *Vulnerable* and one species as *Conservation Dependent* (www.environment.gov.au/epbc/). Seven of these 10 species have been positively identified from within Western Australian waters, including the *Endangered* Northern River Shark (*Glyphis garricki*) and six *Vulnerable* species, i.e. Grey Nurse Shark (*Carcharias taurus*), Great White Shark (*Carcharodon carcharias*), Dwarf Sawfish (*Pristis clavata*), Freshwater Sawfish (*Pristis microdon*), Green Sawfish (*Pristis zijsron*) and the Whale Shark (*Rhincodon typis*) (Morgan *et al.* 2004; Thorburn & Morgan 2004; Thorburn *et al.* 2007, 2008; Stevens *et al.* 2008; Last & Stevens 2009; Pillans *et al.* 2009; Whitty *et al.* 2009a, b). A further species, the Speartooth Shark (*Glyphis glyphis*), which is listed as *Critically Endangered* under the EPBC

Act 1999, is known from near the Western Australian border in the Northern Territory (Pillans *et al.* 2009). Thus, the coastal waters of the Kimberley potentially contains Australia's two *Glyphis* spp., and are also a global hotspot for sawfishes (Pristidae), with four of the world's seven species of pristids found here; these four species comprise all of the known Australian sawfish species.

The pristids are a unique group of ray that are readily identified by the presence of an elongated and flattened rostra possessing enlarged tooth-like denticles known as rostral teeth (Last & Stevens 2009). Globally, all sawfishes have undergone major declines in both range and abundance, largely as a result of their rostral teeth being vulnerable to entanglement in fishing nets (i.e. by-catch), but also through loss of habitat and exploitation, as the rostra are often taken from the fish as curios. The population structures of many of the world's sawfish species are believed to be fragmented (e.g. Simpfendorfer 2000) and there is virtually no information on the sizes of the remaining populations. Four species of pristid, from two genera, are known to occur in Australian waters. In fact, Australia may contain the only remaining viable populations of some of these species, although it is

believed that some species were once distributed more broadly in the Indo-West Pacific region. Each of the four species appears to be broadly distributed in northern Australia, but distributional descriptions are lacking in Western Australia and are based on limited and often localised surveys or from anecdotal reports. However, the northern Pilbara coast and west Kimberley are known to represent an important area for the four species, namely *P. microdon*, *P. clavata*, *P. zijnsron* and the Narrow Sawfish (*Anoxypristis cuspidata*) (Morgan *et al.* 2004; Thorburn *et al.* 2007, 2008; Stevens *et al.* 2008; Last & Stevens 2009; Whitty *et al.* 2009a, b). Although the first three of these species are listed as *Vulnerable* under the EPBC Act, all are protected species within Western Australia under the *Fish Resource Management Act 1994* (FRMA Act), and *P. zijnsron* was listed under *Schedule 1* of the *Wildlife Conservation Act 1950* in Western Australia in 2006. Additionally all are listed as *Critically Endangered* under the IUCN Red List, and are protected from international trade through *Appendix I* of the Convention on International Trade in Endangered Species (CITES). *Pristis microdon* is the only exception, as it is listed under *Appendix II*, allowing for aquarium trade for conservation purposes. *Glyphis garricki*, having only been discovered in Western Australia in 2002 (Morgan *et al.* 2004; Thorburn & Morgan 2004) and formally described in 2008 (Compagno *et al.* 2008), is also protected in Western Australia under the FRMA Act, and is listed as *Critically Endangered* by the IUCN Red List. Collectively, these species represent ~45% (56% if further evidence confirms the existence of *G. glyphis* in the Kimberley) of Australia's elasmobranchs that are listed as *Vulnerable* or higher under the EPBC Act.

It is only very recently that research has been conducted into the ecology of *Pristis* and *Glyphis* species in Western Australia, but it is mostly the result of very localised sampling in only a few selected areas. Recent research on *P. microdon* has largely been confined to the Fitzroy River and King Sound (Thorburn *et al.* 2003, 2004, 2007; Morgan *et al.* 2004; Thorburn & Morgan 2005a; Thorburn 2006; Whitty *et al.* 2008, 2009a, 2009b), while information on *P. clavata* is largely from collections in King Sound and the Fitzroy River estuary (Thorburn *et al.* 2008) or from Hall Point and Cape Keraudren (Stevens *et al.* 2008), and data on *P. zijnsron* are limited to Cape Keraudren (Stevens *et al.* 2008). For *G. garricki*, data are drawn from limited captures in King Sound (Thorburn & Morgan 2004, 2005b; Thorburn 2006; Whitty *et al.* 2008) and that reported in Pillans *et al.* (2009) for the north-eastern Kimberley.

In order to strengthen information on these EPBC listed *Pristis* species, and as we were aware of many instances where rostra were removed from fish and kept as souvenirs, we enlisted the public to provide rostra for examination. The use of donated rostra from various people within different towns and communities of the region and from the recreational, indigenous and commercial fishing sectors is a valuable tool for examining species distributions in this remote part of Australia. Rostra have previously proved useful for the extraction of DNA (Phillips *et al.* 2009a, 2011). These rostra, which are taken as curios, are likely to provide valuable information on each species' spatial demographics that would otherwise take many years to

document through targeted surveying in remote regions over a vast coastline. Utilising the relationship of rostrum length to total length and known size at sexual maturity for the species (e.g. Thorburn *et al.* 2007, 2008; Peverell 2008), this study aims to reconstruct spatial distributions of pristids of various life-history stages from rostra and localised ecological studies in Western Australia. It is hypothesised that the use of rostra from private collections will be a valuable tool to reconstruct species distributions and identify areas which may act as nurseries or provide habitat to mature individuals.

Methods

Data presented here are focussed on northern Western Australian (northern Pilbara and Kimberley) assemblages of the EPBC listed species of *Pristis* and the one species of *Glyphis*, but information from other regions (Peverell 2005, 2008; Pillans *et al.* 2009; Last & Stevens 2009) is used for comparative purposes and to address knowledge gaps. Regional information on these species was collated from both literature reviews (e.g. Thorburn *et al.* 2003, 2004, 2007, 2008; Morgan *et al.* 2004; Thorburn & Morgan 2004, 2005a; Phillips 2006; Phillips *et al.* 2008, 2009b, 2011; Stevens *et al.* 2008; Whitty *et al.* 2008, 2009a, b) and our unpublished data including recent surveys in the region, which has been ongoing since 2001. The fourth Australian species of sawfish, *A. cuspidata* has not been included in this review as (1) it is currently not listed under the EPBC Act and (2) we have virtually no ecological information on the species in the region.

The above studies in Western Australia are, however, generally from very localised sampling, with all but two largely concentrated within the Fitzroy River and parts of King Sound in the south-west of the Kimberley. The exceptions being the genetic studies by Phillips *et al.* (2011) which included samples from throughout Australia, and that by Stevens *et al.* (2008) which included very localised sampling in the Pilbara (Cape Keraudren) and western Kimberley (Hall Point). The above studies therefore, provide only limited information on the spatial distribution of the *Pristis* species in Western Australia.

Sawfish rostra have long been kept as curios in private collections. To overcome the limited spatial extent of targeted surveying for sawfishes, we invited the public to donate or lend rostra for morphological examination. Since 2001 we have examined 283 donated rostra from the three EPBC listed *Pristis* species (see Table 1), including some that were collected during WWII in the Fitzroy River and one held in the collections of the Australian Museum that dated back to 1885 (location unknown). Rostra were readily identified on the basis of a combination of the number of rostral teeth and the tooth morphology (see results and Phillips 2006; Thorburn *et al.* 2007; Last & Stevens 2009). This included 141 that were identified as belonging to *P. clavata*, 74 that were from *P. microdon* and 68 that were from *P. zijnsron*. For 27 (~9%) of these, the original capture location was either unknown or not detailed enough to be of use for distributional data, but most were either supplied with a high degree of accuracy (e.g. to the nearest 1 km) or were from general locations, for example, King Sound, or

Roebuck Bay. A further 52 rostra were from outside of Western Australia (see Table 1). For the purpose of providing distributional data, only those rostra from Western Australia that had accompanying site capture information with a high degree of certainty were used for analyses.

Information on the distribution of sawfishes in Western Australia was thus obtained from the collation of the locations of the 204 rostra that were donated from private collections throughout the region and the targeted surveys during various studies. When considering that the approximate size at sexual maturity of the species is generally known, the size of these rostra also provided valuable information on the spatial extents of potential nursery areas as well as locations utilised by mature animals, which is a major knowledge gap for each of these species and complemented the site specific studies in Western Australia on each of these species. An additional 237 individuals of *P. microdon* have been captured and measured (and tagged) from the Fitzroy River and King Sound between 2002 and 2010, one was reported from Cape Keraudren and another from 80 Mile Beach (see Thorburn *et al.* 2007, Whitty *et al.* 2009a, Morgan & Whitty unpublished data). Chidlow (2007) reported on the capture of one *P. microdon* from Cape Naturaliste within the State's south-west, although this capture is believed to be an anomaly. Ishihara *et al.* (1991a) recorded 10 *P. clavata* in the Pentecost River system. Stevens *et al.* (2008) reported on nine *P. clavata* near Hall Point in the Kimberley, Thorburn *et al.* (2008) provide details on 44 *P. clavata* captured in King Sound (including tidal areas of the larger rivers) between 2002 and 2004, and we captured a further 55 *P. clavata* from King Sound and the Fitzroy River estuary (Morgan & Whitty unpublished data) between 2005 and 2010. We have 17 capture records of *P. zijsron* from Western Australia (McAuley unpublished data), and Stevens *et al.*

(2008) report on 11 *P. zijsron* from the Cape Keraudren region.

Ignoring donated rostra with unreliable site localities or where capture information was unavailable or outside of Western Australia (see Table 1), our review is based on the following:

P. microdon: 55 donated rostra + 240 captures ($n = 304$)

P. clavata: 120 donated rostra + 118 captures ($n = 238$)

P. zijsron: 27 donated rostra + 28 captures ($n = 54$)

Measuring the length of each rostra, together with known size at sexual maturity from the various studies (*e.g.* Peverell 2005, 2008; Thorburn *et al.* 2007, 2008) and total length versus rostral length relationships, has allowed us to create distribution records of the species and assess the spatial extent of potential nurseries, adult habitats and pupping grounds for each species of *Pristis* throughout Western Australia. Species maps of these pristids as well as *G. garrieki*, which are based on the studies by Thorburn & Morgan (2004), Whitty *et al.* (2008, 2009a) and Pillans *et al.* (2009), were created in MapInfo. For clarity, each individual rostra or capture is not necessarily presented on each map, for example, over 200 *P. clavata* were reported from King Sound, and over 200 *P. microdon* were reported from the Fitzroy River.

Morphological measurements included: total length (TL), total rostrum length (TRL; alternatively labelled rostrum length (RL) in some literature (*e.g.* Thorburn 2006; Thorburn *et al.* 2007, Whitty *et al.* 2008)), standard rostrum length (SRL) and weight (WT). TL is the distance from the tip of the rostrum to the tip of the caudal fin (Fig. 1). TRL is the distance from the tip of the rostrum to its base, where the rostrum flares to join the head. The relationship of TL and TRL were used to approximate total lengths from donated rostra. All length and weight measurements are reported in cm and kg, respectively.

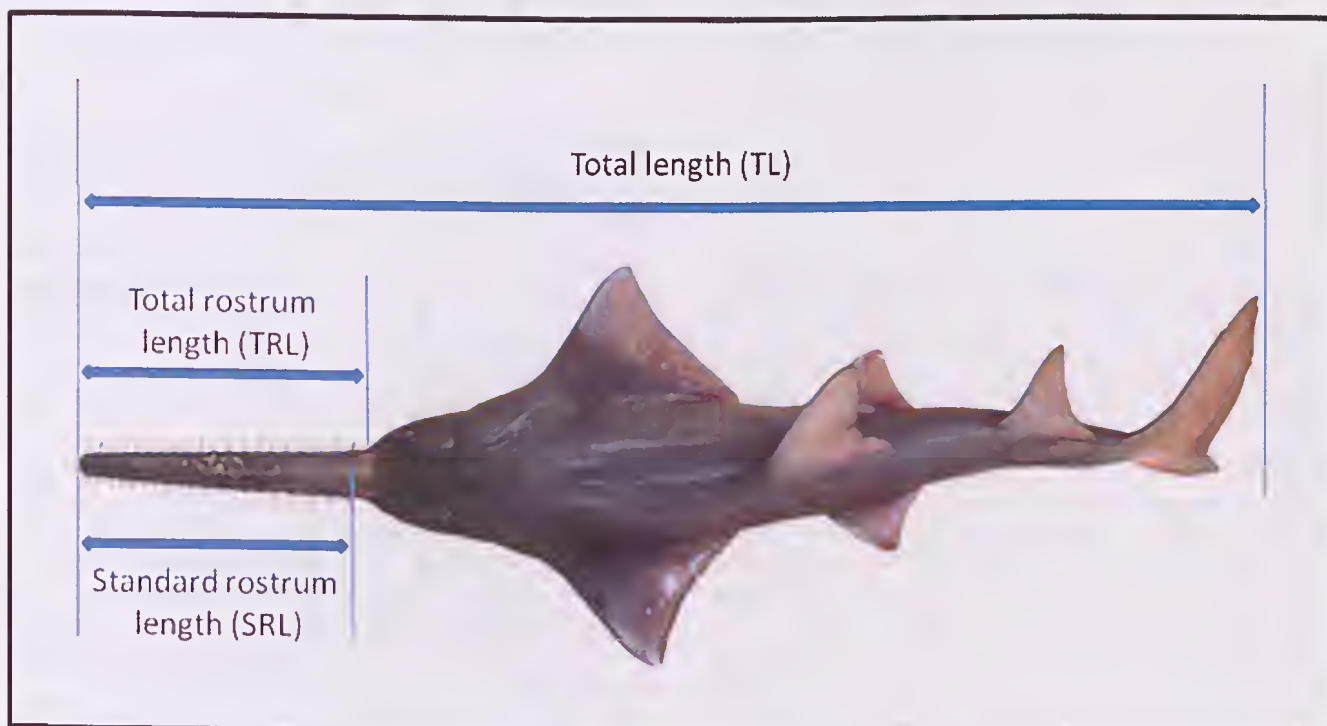


Figure 1. Morphological measurements derived from sawfish captured.

Results and Discussion

Donated rostra as a tool for enhancing research

To date, all targeted sawfish sampling in Western Australia has been restricted to a few specific locations and thus has been unable to provide an indication of their spatial extent in state waters. Rostra from private collections have allowed us to refine the distribution of *Pristis* spp. in Western Australia and have substantially added to scientific collections. For example, although we have records for 386 captures of the three *Pristis* spp. from targeted surveys, a further 283 rostra were donated from the public during this study (Table 1). While ~9% of these were from unspecified locations, and a further 18% were from outside of Western Australian waters; the remaining 205 rostra were useful for examining spatial patterns of the species (see Table 1, Figs 5–7). Donated rostra thus accounted for ~35% of all known records in Western Australia. Many of these rostra were from locations that we previously had no records of sawfish from. Importantly, donated rostra account for ~50% of all records of both *P. zijsron* and *P. clavata* in state waters. Together with known information on the relationship between fish length and rostra length and the length at maturity, we are also able to determine areas that are known adult habitats and juvenile habitats (see below). Based on the known approximate size of newborn pups and the predicted rostrum length from TRL/TL

relationships, we are also able to determine potential pupping areas. Phillips *et al.* (2011) also demonstrated the value in assessing the population genetic structure and genetic diversity of sawfishes from rostra.

Morphology, distribution and ecology of *Pristis* spp. in north-western Australia

Freshwater Sawfish (*Pristis microdon*)

Morphology and recognition

Pristis microdon is a large-sized sawfish, and can be distinguished through the following morphological characteristics: first dorsal fin origin located anterior to the origin of its pelvic fins; base of first dorsal fin greater than that of the second; height of second dorsal fin slightly higher than that of the first; small ventral caudal fin lobe; no terminal notch on dorsal lobe (Taniuchi *et al.* 1991b; Compagno & Last 1999; Last & Stevens 2009); proximal teeth begin in close approximation at the base of the rostra, in Western Australia 17–23 left (Fig. 2) and 34–47 total (Fig. 3) rostral teeth (Thorburn 2006; Thorburn

Table 1

Numbers of rostra donated and their original capture locations for *Pristis clavata*, *Pristis microdon* and *Pristis zijsron* during this study. Fitzroy River includes only rostra from non-tidal reaches. King Sound includes rostra from tidal waters of the Fitzroy and Robinson Rivers. See Figures 5, 6 and 7 for locations.

Site of rostra	<i>Pristis clavata</i> n = 141	<i>Pristis microdon</i> n = 74	<i>Pristis zijsron</i> n = 68
Fitzroy River		41	
King Sound	118	11	3
One Arm Point			1
Cape Leveque			1
Pender Bay			1
Beagle Bay			4
Willie Creek			1
Roebuck Bay	2	2	8
80 Mile Beach		1	1
Port Hedland			2
Whim Creek			2
Karratha			3
Exmouth			1
Coral Bay			1
Western Australia (location unknown)	7	9	11
Queensland	1	3	5
Northern Territory	13	4	17
New South Wales			6
Papua New Guinea		2	
Indonesia		1	

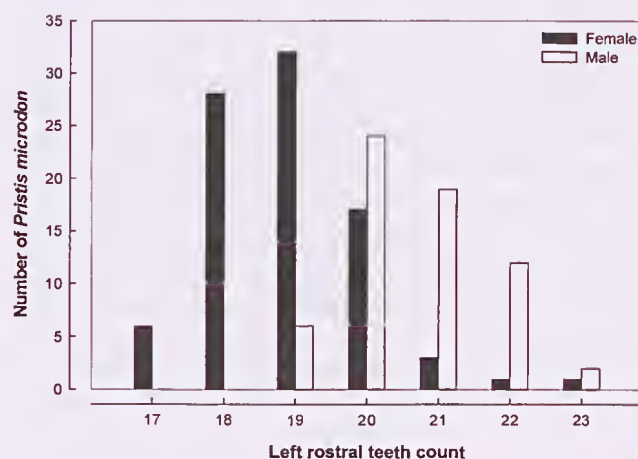


Figure 2. Left rostral teeth count of female and male *Pristis microdon* captured in Western Australia.

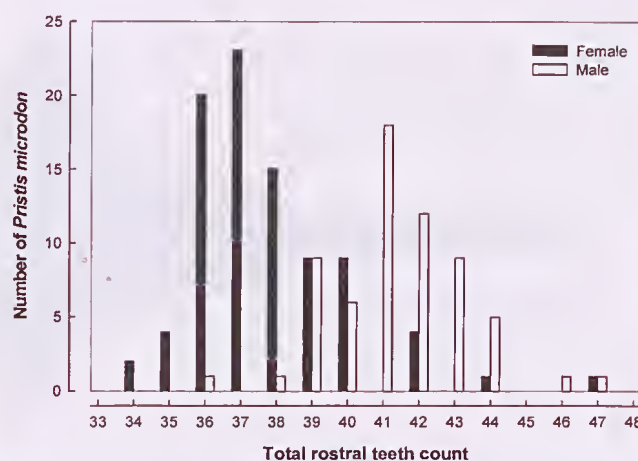


Figure 3. Total number of rostral teeth for female and male *Pristis microdon* captured in Western Australia.

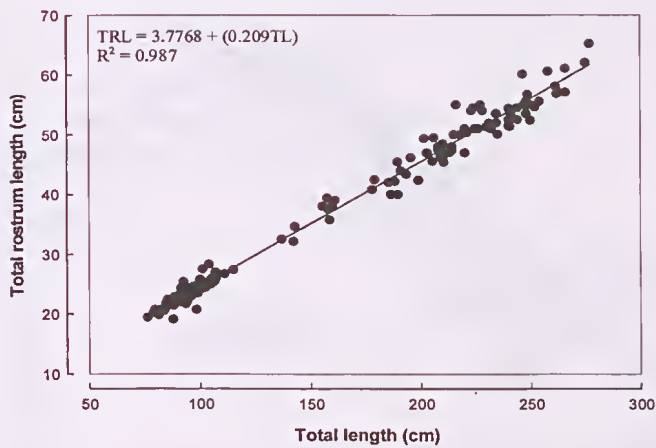


Figure 4. Relationship of total length (TL) to total rostrum length (TRL) of *Pristis microdon* captured in Western Australia.

et al. 2004, 2007, Whitty *et al.* 2008, 2009a); females with 17–23 left rostral teeth, usually ≤ 20 , males with 19–23 rostral teeth (Fig. 2) (Whitty *et al.* 2009a) (also observed by Ishihara *et al.* (1991b) in *P. microdon* collected in other regions of northern Australia and Papua New Guinea); marginal grooves that go to the base of rostral teeth (Phillips 2006, Thorburn *et al.* 2007). Total rostrum length between 21 and 27.5% of TL ($TRL = 3.7768 + (0.209TL)$) (based on *P. microdon* 76–277 cm TL (Fig. 4)). Taniuchi *et al.* (1991b) documented this range to be $\sim 25\%$ for *P. microdon* (99.2–108.4 cm TL) outside of Western Australia. Of the Australian specimens, the rostrum of *P. microdon* is most similar to *P. clavata*. These species can best be separated by position of the first dorsal fin and presence of a lower caudal lobe on *P. microdon*. Additionally, the degree in which the grooves on the posterior margin of the rostral teeth extend down the teeth to the junction with the rostrum blade is a useful tool to distinguish *P. clavata* from *P. microdon* (see Thorburn *et al.* 2007).

Life history

Born between 72 and 90 cm TL (Compagno & Last 1989; Peverell 2005; Thorburn *et al.* 2007; Peverell 2008; Whitty *et al.* 2009a), *P. microdon* are estimated to attain maximum lengths of 600–700 cm TL (Peverell 2008; Last & Stevens, 2009), with the largest recorded individual being 656 cm TL (Compagno & Last 1999). In Western Australia, the Fitzroy River appears to be the most important nursery area for this species, where male and female juveniles have been recorded at between 76.3–235 cm and 78.9–277 cm TL, respectively (Thorburn *et al.* 2003, 2007; Whitty *et al.* 2009a; this study).

Last and Stevens (2009) provide details on the global distribution of *P. microdon* and note the uncertainty of describing an accurate contemporary distribution due to localised extinctions; but do confirm their presence from several major river systems in Indonesia and New Guinea, and the species is also likely to occur in India and eastern Africa (Taniuchi *et al.* 2003; Skelton 2001). Rostra donated in this study further support their occurrence in New Guinea and Indonesia. Within Western Australia, *P. microdon* has been found from Cape Naturaliste (Chidlow 2007) in the south-west (a single specimen), to the Ord River (Gill *et al.* 2006) in the north.

However, most have been recorded from the west Kimberley (Fig. 5), specifically the Fitzroy River, which is arguably one of the most important nursery areas known (Thorburn *et al.* 2003, 2004, 2007; Morgan *et al.* 2004; Thorburn & Morgan 2005a; Whitty *et al.* 2008, 2009a) (Fig. 5). Within the freshwaters of the Fitzroy River, all *P. microdon* are thought to be immature, with few immature fish located elsewhere in Western Australia (Fig. 5). The only confirmed records of immature *P. microdon* from Western Australia outside of the Fitzroy River and the other major tributaries of the King Sound are from donated rostra, and include Willie Creek north of Broome ($n = 1$), and in Roebuck Bay ($n = 2$) near Broome, although Thorburn *et al.* (2003) and Gill *et al.* (2006) provide anecdotal evidence that they are in the Ord River (Fig. 5). Males and females of *P. microdon* mature at ~ 300 cm TL, although males potentially mature at a slightly smaller size (Compagno & Last 1998; Thorburn *et al.* 2007; Peverell 2008; Whitty *et al.* 2008). Distribution of mature individuals (see below) known from captures and donated rostra (*i.e.* at >300 cm TL, their rostrum length would be >65 cm (Fig. 4)), in Western Australia have only been recorded from Cape Naturaliste (not illustrated) (Chidlow 2007), Cape Keraudren, 80 Mile Beach, Roebuck Bay (near Broome) and King Sound (Fig. 5). Dispersal in females is thought to be philopatric (see Phillips *et al.* 2009b, 2011), where the females may return to their natal river to pup. It is plausible that each of those larger females found along 80 Mile Beach and in Roebuck Bay (see Fig. 6), may move to the mouth of the Fitzroy River to pup.

Using vertebral analysis, Thorburn *et al.* (2007) estimated *P. microdon* in Western Australia of 100 cm, 140–160 cm, 180–220 cm, and 230–280 cm TL to be around one, two, three and four years of age, respectively. Also using vertebral analysis, Peverell (2008) produced similar age estimates, finding that Queensland *P. microdon* ranging between 83–101 cm, 119–140 cm, 143–180 cm, 170–219 cm, 229–253 cm and 234–277 cm TL were in their 1st, 2nd, 3rd, 4th and 5th year of life, respectively. Peverell (2008) also found a 582 cm TL female to be 28 years of age. Peverell (2008) calculated a k -value of 0.08 year^{-1} ($L_{\infty} = 638 \text{ cm TL}$, $t_0 = -1.55 \text{ years}$), estimating growth within the first year to be 52 cm, and growth in the fifth year to be 17 cm.

Limited information suggests that *P. microdon* pup annually with litters of 6–12 pups (Peverell 2008). While it is unknown where breeding occurs in Western Australia, the presence of small juveniles with umbilical scars indicates that at least one of the pupping grounds is in close approximation to the river mouth area of the Fitzroy River. From catches in the Fitzroy River, pupping is likely to occur in the wet season (January to April) (Whitty *et al.* 2008, 2009a). Size and duration of the wet season are likely to be positively correlated with survival of 0+ *P. microdon*, as a prolonged and/or very wet season would increase their ability to access more stable upstream pools and thereby decrease the risk of predation from large bodied predators (*e.g.* Bull Shark (*Carcharhinus leucas*) and Estuarine Crocodile (*Crocodylus porosus*)) (Thorburn *et al.* 2007, Whitty *et al.* 2008, 2009a). Juveniles have been recorded in pools of the Fitzroy River that are well in excess of 300 km from the alleged pupping sites in the river mouth (Morgan *et al.* 2004).

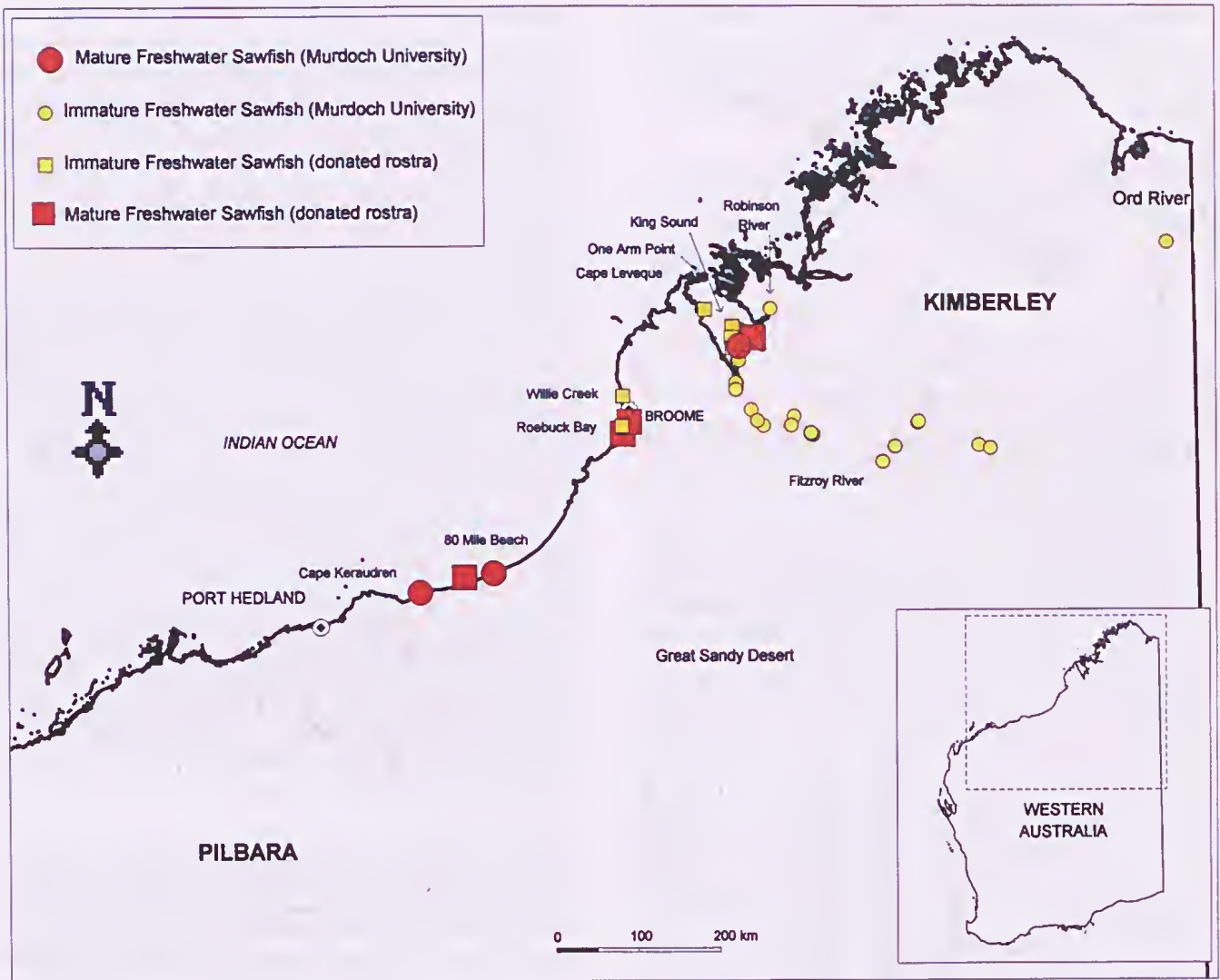


Figure 5. Catches of *Pristis microdon* in the northern Pilbara and Kimberley region of Western Australia, indicating maturity status (from Murdoch University and donated rostra). N.B. Chidlow (2007) reports on the capture of a mature male near Cape Naturaliste in south-western Australia. Data from Morgan *et al.* (2004), Thorburn *et al.* (2004, 2007), Gill *et al.* (2006), Whitty *et al.* (2008, 2009a, b), Phillips *et al.* (2008) and this study.

Dwarf Sawfish (*Pristis clavata*)

Morphology and recognition

Pristis clavata can be distinguished by the following morphological characteristics: origin of first dorsal fin in line or just posterior with that of the pelvic fin (Ishihara *et al.* 1991a; Compagno & Last 1999; Last & Stevens 2009); second dorsal fin only slightly lesser in size than the first (Ishihara *et al.* 1991a); no ventral caudal lobe (Compagno & Last 1999; Last & Stevens 2009); proximal rostral teeth begin near base of rostrum (Compagno & Last 1999); in Western Australia 19–22 left rostral teeth, 38–45 total rostral teeth, no significant difference between male and female teeth counts (Thorburn 2006; Thorburn *et al.* 2008); marginal grooves on rostral teeth that generally do not extend to the tooth base in juveniles and most adults (Phillips 2006; Thorburn 2006; Thorburn *et al.* 2007, 2008). In Western Australia, TRL has been recorded to range between 19.0–21.2% of the TL for *P. clavata* ranging from 80.2–140.2 cm TL (Ishihara *et al.* 1991a). Thorburn *et al.* (2008) recorded TRL to average 20.1% (± 0.001 SE) of TL in *P. clavata* ranging from 80–250 cm TL (TRL = 0.6142

TL^{0.8475}). This range may increase with the addition of smaller individuals (*i.e.* neonates) when considering that the holotype of the species (61.9 cm TL), had a TRL of ~25% of TL (Garmon 1906).

Life history

Pristis clavata is pupped at between ~60 and 81 cm TL and estimated to reach at least 310 cm TL (Peverell 2008; Last & Stevens 2009), making it the smallest of Australia's *Pristis* spp.

Last and Stevens (2009) suggest that *P. clavata* is restricted to northern Australia from Cairns to 80 Mile Beach, and that it is now rare in Queensland, however Peverell (2008) suggests that within Queensland, the species is restricted to the Gulf of Carpentaria. In Western Australia the majority of capture locations and donated rostra for *P. clavata* are from the King Sound and the lower reaches (tidally influenced) of its tributaries, *i.e.* Fitzroy River, May River and Robinson River, as well as from near Walcott Inlet in the Kimberley as well as Cape Keraudren and 80 Mile Beach in the northern Pilbara/

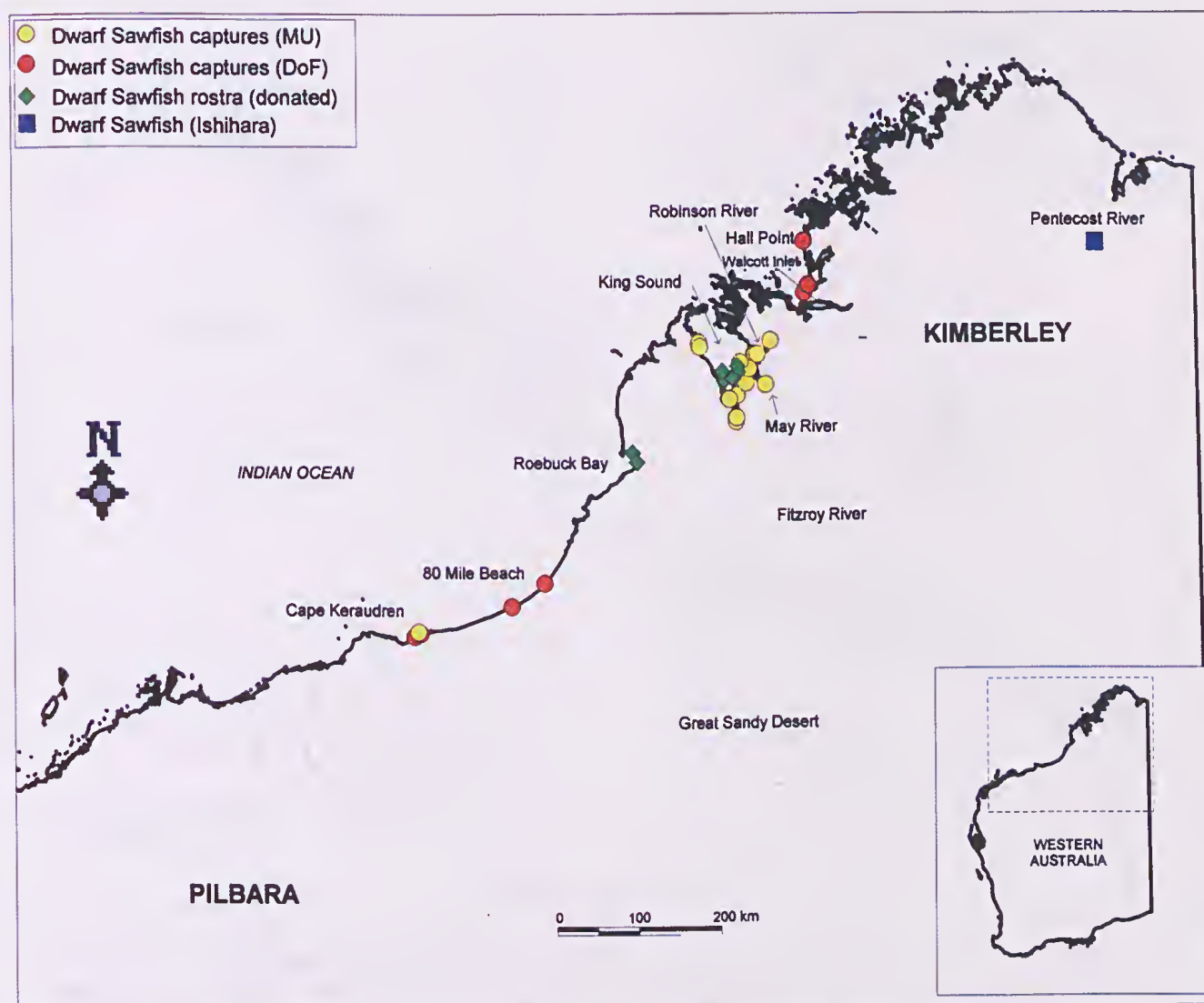


Figure 6. Capture locations of *Pristis clavata* in Western Australia (data derived from CFFR, Murdoch University (MU), Department of Fisheries (DoF), Stevens *et al.* (2008), Ishihara *et al.* (1991a) and rostra donated to this study). N.B. Donated rostra from King Sound are represented on the map by only a few samples, and are actually considerable in number (>100). DoF includes data presented in Stevens *et al.* (2008).

southern Kimberley (Table 1, Fig. 6) (this study; Thorburn *et al.* 2003, 2008; Stevens *et al.* 2008). Ishihara *et al.* (1991a) recorded *P. clavata* in the Pentecost River system. While the majority of captures are from shallow, tidally influenced systems, some captures from considerably deeper water (trawls) have been reported (Stephenson & Chidlow 2003).

Pristis clavata has been estimated to reach maturity at around 255–260 cm TL (Last & Stevens 2009). This is supported by the observations of male *P. clavata* in King Sound measuring 194, 219 (this study) and 233 (Thorburn *et al.* 2008) cm TL to have semi-calcified claspers, while males measuring 295 and 306 cm TL had fully calcified and elongated claspers (Peverell 2005). Age of female maturity is uncertain. Capture sites for rostra donated during this study were very localised, with a total of 109 from the King Sound and three from Roebuck Bay (Table 1, Fig. 6). In terms of mature fish, based on a length at maturity of ~240 cm, which corresponds to a total rostrum length of ~45 cm, mature individuals have been recorded from Hall Point in the north to Cape Keraudren

in the south. The vast majority of catches and donated rostra have, however, been from the King Sound (Fig. 6). The smallest individuals recorded have been caught at the Fitzroy River mouth ($n = 5$, TRL <21 cm, TL <100 cm), while a further four donated rostra <21 cm in length came from the King Sound. A further three small individuals (TRL <25 cm) from 80 Mile Beach were recorded by the Department of Fisheries, Government of Western Australia.

Using vertebral ring counts ($n = 5$), and assuming annuli correspond to one years growth, Thorburn *et al.* (2008) estimated *P. clavata* of 90 cm TL in the King Sound to be of one year of age, of 110–120 cm TL to be of two years of age and that of 160 cm TL to be of three years of age. These estimations were in close congruence with that of Peverell (2008) for Gulf of Carpentaria fish.

Information about the population structure of *P. clavata* in Australian waters is limited to Phillips *et al.* (2011) and was based upon nucleotide sequence variation from a portion of the control region in the mitochondrial genome, suggesting that *P. clavata* may be genetically

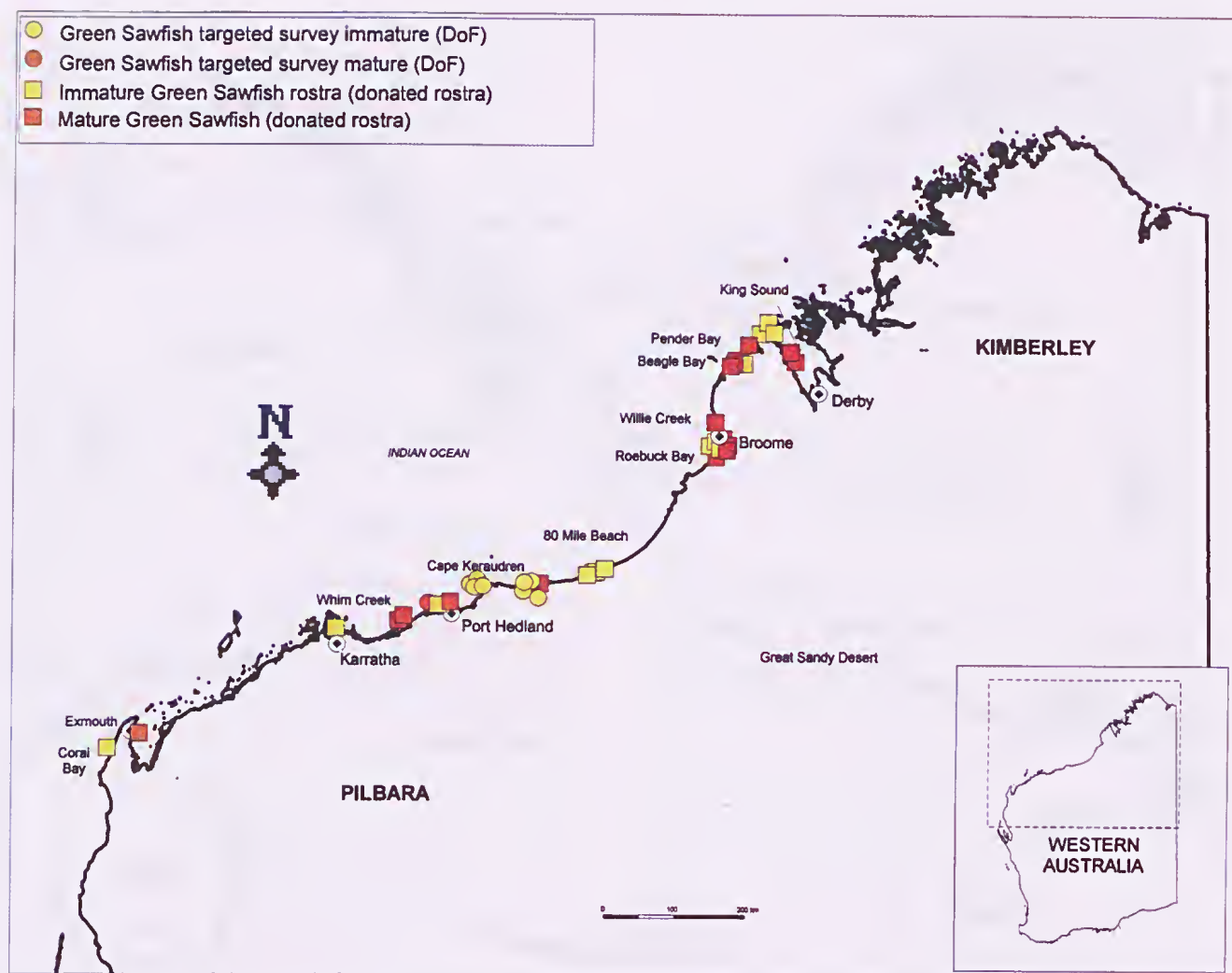


Figure 7. Locations of *Pristis zijsron* in Western Australian waters (data derived from CFFR, Murdoch University, Department of Fisheries (DoF), Stevens *et al.* (2008) and donated rostra from this study).

subdivided between the west coast of Australia and the Gulf of Carpentaria, although this comparison was not statistically significant (see Phillips *et al.* 2011). As assemblages of *P. microdon* and *P. zijsron* from the west coast and the Gulf of Carpentaria were found to be genetically distinct, *P. clavata* is probably also differentiated between these regions (Phillips *et al.* 2011).

Green Sawfish (*Pristis zijsron*)

Morphology and recognition

Pristis zijsron can be distinguished through the following morphological characteristics: origin of first dorsal fin in line or just posterior with that of the pelvic fin (Compagno & Last 1999); dorsal fins large and similar in width and height; ventral lobe of caudal fin minimal, less than half the length of the dorsal lobe (Last & Stevens 2009); no subterminal notch (Compagno & Last 1999); proximal rostral teeth begin near base of rostrum; 23–34 pairs of rostral teeth (Compagno & Last 1999; Last & Stevens 2009); relatively (*c.f.* other Australian sawfishes) extreme tapering of tooth interspaces with proximity to the tip of the rostra (posteriormost tooth gap 2–7 times that of the anteriormost gap) (Compagno & Last 1999;

Last & Stevens 2009); groove on posterior margin of rostral teeth prominent in adults, but lacking in juveniles (Compagno & Last 1999). TRL is 24–30.6% of TL based on nine *P. zijsron* sourced from throughout the Indian Ocean, and ranging between 71 cm and 342 cm TL ($TRL = 0.2825 TL - 3.7389$) (Faria 2007). *Pristis zijsron* is most easily distinguished from the other sawfishes by a greater TRL:TL ratio and by the relatively extreme tapering of tooth interspace with progression towards the distal end of the rostra.

Life history

Last and Stevens (2009) state that *P. zijsron* is widely distributed in the Indian Ocean *e.g.* South Africa, India, Indonesia and Australia. They indicate that the Australian distribution extends from Sydney north and west to Coral Bay (near Exmouth) in Western Australia, with a single record off South Australia; however a decline in southward range on the east Australian coast is alleged to have occurred, to the point that it is now presumed extinct in New South Wales waters. In Western Australia there have been limited studies on the species, but from donated rostra, *P. zijsron* has been recorded from Coral Bay and the Exmouth Gulf to the

Western Australia/Northern Territory border. However, the majority of capture locations are between Karratha and One Arm Point (Fig. 7), with very few specimens ($n = 3$) recorded in King Sound, which is in stark contrast to *P. microdon* and *P. clavata*. Most captures of the species have been from near-shore waters, however, interactions have been reported from the Pilbara Fish Trawl Fishery, which operates in depths between 30 and 200 m (Stephenson & Chidlow 2003). Unlike *P. microdon*, *P. zijssron* does not move into freshwaters and its life-cycle is completed in the marine environment. Based on data obtained from donated rostra, mature *P. zijssron* (>300 cm TL, having a TRL >81 cm) in Western Australia are widespread and are currently known from Exmouth Gulf, Whim Creek, Port Hedland, 80 Mile Beach, Roebuck Bay, Willie Creek, Beagle Bay, Pender Bay, King Sound (including Goodenough Bay) (Table 1, Fig. 7). A further two individuals (>400 cm TL) were recorded by Stephenson and Chidlow (2003) in offshore waters of the Pilbara. The largest *P. zijssron* in our records was from Beagle Bay, which had a rostrum length of 165.5 cm, which would equate to a fish of ~ 600 cm in TL (Fig. 7). The smallest recorded *P. zijssron* in our collections originated at: Roebuck Bay (TRL = 16 cm and 22 cm), Karratha (TRL = 22.3 cm), Cape Leveque (TRL = 26.2 cm), One Arm Point (TRL = 27.3 cm), 80 Mile Beach (TRL = 30 cm), Cape Keraudren (TRL = 31 cm), Port Hedland (TRL = 32.0 cm) and Coral Bay (TRL = 32.2 cm) (Fig. 7), and are presumed to be new recruits. Additionally, Stevens *et al.* (2008) recorded a number of small juveniles near Cape Keraudren (at the southern end of 80 Mile Beach), which ranged in total length from 100 to 212 cm, with four <120 cm TL. These small individuals at 100, 107 ($n = 2$) and 111 cm TL would have had rostrum lengths of <30 cm. Conservatively assuming 0+ *P. zijssron* are <130 cm TL, these captures suggest pupping occurs from at least Coral Bay in the south to at least One Arm Point in the north of Western Australia; however, there are limited data for the north Kimberley coast and they are likely to be more prevalent between Karratha and the Exmouth Gulf (Fig. 7).

Vertebral analysis for aging demonstrated that *P. zijssron* of 83–102 cm ($n = 8$), 128 cm ($n = 1$), 157–166 cm ($n = 2$), 220 cm ($n = 1$), 254–257 cm ($n = 2$), 380 cm ($n = 1$), 438 cm ($n = 1$), 449 cm ($n = 1$), and 482 cm ($n = 1$) TL are likely to belong to the 0+, 1+, 2+, 3+, 5+, 8+, 10+, 16+ and 18+ age classes, respectively (Peverell 2008). *Pristis zijssron* attains a total length of at least 540 cm (Peverell 2005, 2008), with reports as large as 760 cm TL (Last & Stevens 2009).

In Queensland, *P. zijssron* pups in January (wet season) (Peverell 2005). Litter size is approximately 12 (Last & Stevens 2009). Male and female *P. zijssron* mature around 300 cm TL (~ 9 years of age) (Last & Stevens 2009). This was supported with the observation of a pregnant 458 cm TL female (Compagno & Last 1999) as well as a mature 380 cm TL female in Queensland (Peverell 2005).

The population structure of *P. zijssron* was assessed using nucleotide sequence variation in a portion of the mitochondrial control region, which is maternally inherited (Phillips *et al.* 2009b, 2011). The assessment demonstrated that this species is genetically sub-divided across northern Australia, with significant structure found between the west coast and the Gulf of Carpentaria (Phillips *et al.* 2009b, 2011).

Distribution and ecology of *Glyphis* spp. in north-western Australia

The two Australian species of *Glyphis* were only formally described in 2008 (see Compagno *et al.* 2008), and a review of these species was compiled by Pillans *et al.* (2009). Only one species, *G. garricki*, is confirmed from Western Australia, however, it is possible that *G. glyphis* occurs in at least the east Kimberley.

Northern River Shark (*Glyphis garricki*)

Morphology and recognition

Glyphis garricki is a medium-large carcharinid (whaler shark), that can be distinguished through the following morphological characteristics: greyish dorsal and white ventral colorations; border of the ventral and dorsal surfaces, referred to as the watermark boundary or waterline (Compagno *et al.* 2008), exists approximately an eye diameter below the orbit (Compagno *et al.* 2008); no discernible black demarcations, with exception of minor dusky tip on the terminal caudal lobe and faint black coloration on apex of terminal margin and ventral caudal lobe (Compagno *et al.* 2008); head fairly elongated, sloping and rounded (Compagno *et al.* 2008); small eyes, ranging from between 0.77% and 1.03% of the TL (Thorburn & Morgan 2004, Thorburn 2006) or 0.83–1.09 cm in length (Compagno *et al.* 2008); first dorsal fin triangular in shape (Thorburn 2006; Compagno *et al.* 2008); second dorsal fin 58–66% the height of the first (Thorburn & Morgan 2004; Compagno *et al.* 2008); pectoral fins large and slightly curved with narrow bases (Thorburn 2006; Compagno *et al.* 2008); anal fin is only slightly smaller (72–84%) in size compared to second dorsal, with the fin origin marginally posterior to that of second dorsal fin (Thorburn 2006; Compagno *et al.* 2008), lacks a notch observed in other similar species like *C. leucas* and Pigeye Shark (*Carcharhinus ambionensis*) (Field *et al.* 2008); asymmetric caudal fin, with a narrow and longer dorsal caudal lobe (*c.f.* ventral caudal lobe); subterminal notch present (Thorburn 2006; Compagno *et al.* 2008); no pre, inter or postdorsal ridge (Thorburn 2006); longitudinal pre-caudal pit (Compagno *et al.* 2008); upper jaw tooth count of 31–34; lower jaw tooth count of 30–35 (Last & Stevens 2009); upper teeth broadly triangular, lower teeth slender, slightly curved back with spear-like tips (Thorburn 2006; Compagno *et al.* 2008). Most similar in appearance to *G. glyphis*, but can be visually distinguished by the location of the waterline, which crosses just below the orbit in *G. glyphis*. *Glyphis garricki* is often confused with *C. leucas* and *C. ambionensis*, but can be differentiated from these species by its large second dorsal fin, and longitudinal triangular precaudal pit (*c.f.* crescentic precaudal pit) (Compagno & Niem 1998; Compagno *et al.* 2008).

Life history

Pupped at 50–60 cm, *G. garricki* are estimated to reach up to 300 cm TL (Stevens *et al.* 2005; Last & Stevens 2009). The largest recorded capture of *G. garricki* in Australian waters is a 251 cm TL female, but in Western Australia the largest male and female recorded is 142 cm TL (18.64 kg) and 135 cm TL (16.83 kg), respectively (Thorburn & Morgan 2004; Thorburn 2006).

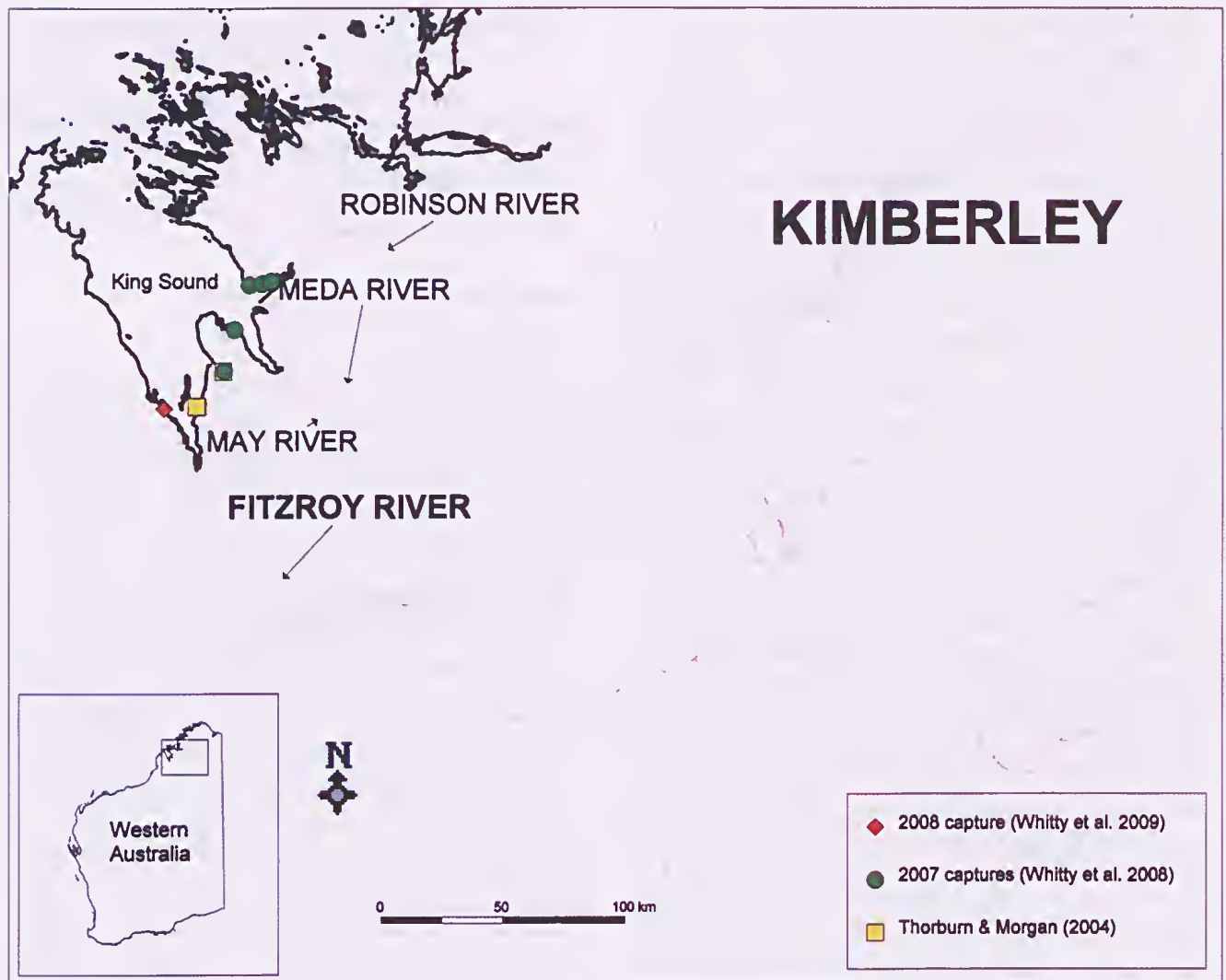


Figure 8. Known capture locations of *Glyphis garricki* in the west Kimberley (from Thorburn & Morgan 2004; Whitty *et al.* (2008, 2009a)). See Pillans *et al.* (2009) for the distribution of the species in the east Kimberley.

Vertebral counts of 137–151 (precaudal = 73–83) in Australian waters (Compagno *et al.* 2008; Last & Stevens 2009); 140–151 (avg = 146 (+1.53 SE) in the King Sound (Thorburn & Morgan 2004). Fusion of vertebrae was documented in three *G. garricki* (99 cm TL male, 142 cm TL male, 135 cm TL female) captured in the King Sound in 2002 and 2003 (Thorburn & Morgan 2004; Thorburn 2006). Thorburn and Morgan (2004) hypothesised this possibly was due to inbreeding associated with a small genetically effective population size, but not necessarily a small census size.

In Western Australia the majority of capture locations for *G. garricki* are in the King Sound in the west Kimberley (Fig. 8) (see Morgan *et al.* 2004; Thorburn & Morgan 2004, 2005b; Whitty *et al.* 2008, 2009a), however, recent collections have also occurred in the Ord River mouth and Joseph Bonaparte Gulf (Last & Stevens 2009; Pillans *et al.* 2009). Most collections in Western Australia have occurred in turbid, macrotidal mangrove systems of the King Sound in salinities >20 ppt over sandy or silty substrates. Also known from a few locations in the Northern Territory (Field *et al.* 2008; Pillans *et al.* 2009).

Pillans *et al.* (2009) provided records of 32 individual *G. garricki* from marine, estuarine and freshwater habitats in Western Australia and the Northern Territory, including 13 from the King Sound (Thorburn & Morgan 2004) and a further 11 from the north-eastern Kimberley in the King River ($n = 3$), Joseph Bonaparte Gulf ($n = 6$), and the Ord River ($n = 2$). A further 12 individuals have since been recorded in King Sound (this study) and thus ~82% of all known captures of this rare species in Australia are from Western Australia, and 50% are from King Sound.

Little is known about the age and growth of *G. garricki*. Initial aging work by Tanaka (1991) estimated a 131 cm TL female in the Northern Territory to be four years of age. Using this information with an estimated pupping size of 50–60 cm TL, growth in the first four years was estimated to average 19 cm year⁻¹ (Stevens *et al.* 2005).

Litter size has been shown to be approximately nine (Stevens *et al.* 2005; Pillans *et al.* 2009). Stevens *et al.* (2005) estimated maturity to occur between 170 and 200 cm TL, based on the assumption that *G. garricki* has a similar growth rate to *C. leucas*. In King Sound, males of 99.4 (Thorburn & Morgan 2004) and 109 cm TL (Whitty *et al.*

2009) were found to have semi-calcified claspers (i.e. were maturing), whereas a 136.5 cm TL (Whitty *et al.* 2009a) and a 141.8 cm TL male (Thorburn & Morgan 2004; Thorburn 2006) were found to be mature, suggesting the estimate from Stevens *et al.* (2005) was high, or at least not accurate for males in the west Kimberley. Female maturity likely occurs at a size <177 cm TL as one female of this size was recorded to contain nine embryos (Last & Stevens 2009). Females between 147 and 157 cm TL ($n = 4$) were found to be immature (Stevens *et al.* 2005), supporting the view that maturity occurs above this size.

The only genetic study for *G. garricki* is that by Wynen *et al.* (2009). This was essentially performed to determine the extent and nature of genetic differences between the different *Glyphis* spp. Virtually nothing is known about the population structure of *G. garricki* in Australian waters. Wynen *et al.* (2009) assessed whether variation in a 500 bp fragment of the mitochondrial control region was sufficient to detect genetic differentiation within *Glyphis* species across northern Australia, however, no genetic variation was found in *G. garricki* despite samples from Western Australia and the Northern Territory (Wynen *et al.* 2009). It was concluded that more variable markers, such as microsatellite loci, would be necessary to investigate the population genetics of this species (Wynen *et al.* 2009), although the sample size used in this assessment was very small ($n = 2$; see Wynen *et al.* 2009).

General threats to the species

Peverell (2008) proposed that the Gulf of Carpentaria offers refuges for sawfishes on the basis that it is relatively undisturbed in terms of coastal development with low levels of habitat degradation and a multitude of spatial and temporal fishing closures. This could also be applied to the northern Pilbara and most of the Kimberley which is sparsely populated and relatively pristine, and where commercial fisheries are at a relatively low level with considerable restrictions. Furthermore Phillips *et al.* (2011) suggest that both *P. clavata* and *P. zijsron* have genetically 'healthy' populations on the west coast while genetic diversity of these species is reduced in the Gulf of Carpentaria. The threats to these species are, however, varied, and while they are highly susceptible to entanglement in fishing nets, their fins are greatly valued in the international fin trade as are their rostra, which are often taken as souvenirs (Bigelow & Schroeder 1953; Camhi *et al.* 1998; Seitz & Poulakis 2006). However, all Australian *Pristis* spp. are now protected in Australian waters and there are no direct fisheries for this group, although by-catch of *Pristis* spp. does occur in several fisheries (Stephenson & Chidlow 2003; McAuley *et al.* 2005; Peverell 2005; Field *et al.* 2008). Stevens *et al.* (2005) reported the gill net fisheries to have the highest percent of *Pristis* by-catch (80.2%), followed by trawling (16.6%), line (9.2%) and recreational gears (0.3%). In Western Australia, a range of 0.7–1.1 t (live weight) of *P. microdon* was estimated to be captured in the northern regions of the Kimberley Gillnet and Barramundi Managed Fishery (KGBMF; excluding the Broome and Eighty Mile Beach area) in 2000–2004 (McAuley *et al.* 2005). Their distribution in the Ord system has been impacted by the regulation of the

system (Doupé *et al.* 2005) and in the Fitzroy River by the Camballin Barrage (Morgan *et al.* 2005). For *P. clavata* it was estimated that in 2000–2004, tonnage of *P. clavata* captured ranged from 2.6–6.5 t (live weight) in the Broome and Eighty Mile Beach Area, and ranged from 6.6–11.1 t (live weight) in the more northern regions of the Kimberley Gillnet and Barramundi Managed Fishery (McAuley *et al.* 2005). In 2000–2004, tonnage of *P. zijsron* captured was estimated to range between 5.3 and 9.6 t (live weight) in the Broome and Eighty Mile Beach Area (McAuley *et al.* 2005) and 4 t in the Pilbara Fish Trawl Fishery in 2001 which operates in ~50–200 m depth (Stephenson & Chidlow 2003). The high number of rostra obtained during this study (283) suggests that there is also an unsubstantiated harvest in the various fishing sectors in northern Western Australia. *Glyphis garricki* are potentially impacted on by a very low level of commercial gill-netting, but no information exists on this.

Conclusions

For the pristids, the species catch data together with data obtained from the donated rostra and the relationship of TL to TRL for each species, were valuable in constructing the most comprehensive distribution maps of these species in Western Australia. These data were also valuable in identifying the regions where mature fish were present, as well as identifying potential nursery areas of the different species (e.g. Figures 5 and 7). The use of donated rostra has reduced biases on distributions that were generated from targeted surveys in limited areas.

Results from this study indicate that newborn pups of *P. microdon* are restricted to the mouths and freshwaters of the major catchments within the King Sound. No other rivers sampled in Western Australia have been found to host juvenile *P. microdon*. In contrast, newborn pups of *P. clavata* are only known from the mouth of the Fitzroy River (tidal waters), King Sound and 80 Mile Beach. With regard to *P. zijsron*, pupping locations appear far more widespread and pups have been found at a number of coastal locations between Karratha and Cape Leveque. In general the proposed nurseries are all shallow, near-shore habitats often in close proximity to river mouths. Using these habitat types as nursery areas would likely decrease the risk of predation by larger marine predators (Heupel *et al.* 2007). The records of numerous juvenile *P. microdon*, *P. clavata* and *G. garricki* within the Fitzroy River and/or King Sound, suggests that this area is important for the maintenance of these species in Western Australia. The Fitzroy River itself is arguably one of the most important *P. microdon* nurseries throughout their known range. Additionally, using rivers as nurseries would limit the interaction of pups with near-shore gill net fisheries. The Fitzroy River offers highly seasonal and predictable flow regimes giving continuity of habitats throughout the seasons, unlike many rivers of the Pilbara where rainfall and river discharge are sporadic (Morgan & Gill 2004). Immensity of river discharge and increases in stage height during the wet season in the Fitzroy, likely adds to the success of the species in the river, due to the intrinsic relationship between the size of the wet season and recruitment/survivorship of freshwater and estuarine fishes (Mills &

Mann 1985; Drinkwater & Frank 1994) including *P. microdon*. Additionally the intricate and abundant tidal mangrove systems, river estuaries, and rivers of King Sound provide ideal nursery areas for *P. clavata* and *G. garricki* (N.B. *G. garricki* neonates and juveniles are occasionally found in freshwater (Taniuchi *et al.* 1991a; Pillans *et al.* 2009), but they have not been recorded in freshwater in Western Australia).

Similar to the range of 0+ *P. zijssoni*, mature *P. zijssoni* are known from Whim Creek to King Sound. On the other hand, mature *P. microdon* appear to be less widespread, being known from 80 Mile Beach (Cape Keraudren) to King Sound. Mature *P. clavata* are similarly distributed to *P. zijssoni*, being found from Hall Point to Cape Keraudren, albeit in low numbers. The majority of known records of mature *P. clavata*, based largely on rostral collections, have originated from King Sound. The tidal mangrove systems of King Sound are important nurseries for *P. clavata* and also *G. garricki*, with the mouths of tidal creeks in King Sound being the only known habitats for *G. garricki* in the west Kimberley, where 50% of all Australian records of the species have come from.

The increase in development of the Kimberley and subsequent human population growth will inevitably lead to a decline in the viability of these species, particularly if migration paths are reduced (e.g. by barriers in the Fitzroy River as has occurred in the Ord River (see Doupé *et al.* 2005)) or by an increase in interactions with recreational and commercial fishers. There are knowledge gaps in terms of the distribution and target surveys are required between King Sound and the Ord River.

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Inter-nesting distribution of green turtles (*Chelonia mydas*) and flatback turtles (*Natator depressus*) at the Lacepede Islands, Western Australia

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Abstract

The inter-nesting distributions of green (*Chelonia mydas*) and flatback (*Natator depressus*) turtles nesting at the Lacepede Islands, off the Kimberley coast of Western Australia, were studied during the 2009–2010 nesting season. Twenty-two satellite transmitters were attached to green and flatback turtles nesting on the West Island rookery; of these, inter-nesting data were received for 10 green and 5 flatback turtles. Turtles were tracked for 20–83 days during inter-nesting. Key findings from this study indicate that flatback turtles generally have a broader inter-nesting distribution than green turtles. All flatback turtles travelled at least 26 km from the nesting beach during inter-nesting, whereas only 2 of the 10 green turtles travelled more than 10 km from the nesting beach. Individuals of both species travelled to within 5 km of the Western Australian mainland coast during inter-nesting. This study has also demonstrated that satellite transmitters can be successfully deployed on green and flatback turtles early in the nesting season without significant data loss due to transmitters being damaged by nesting and inter-nesting behaviours.

Keywords: inter-nesting, green turtles, flatback turtles, satellite telemetry, Lacepede Islands, Kimberley region.

Introduction

Western Australia's nesting populations of green and flatback turtles are thought to be amongst the largest in the world (Limpus 2009). While major rookeries have been identified (see Prince 1994; Limpus 2009), little is known about the inter-nesting movements of flatback and green turtles within Western Australia (Pendoley 2005). With increasing tourism and industrial development along Western Australia's coastline and offshore islands it is important to understand the inter-nesting distributions of Western Australia's marine turtle populations, so that potential impacts to these turtles can be understood and managed (Limpus 2009; Waayers 2010). Understanding differences in inter-nesting behaviours between species sharing the same nesting beaches is also important, to provide rationale for species-specific management decisions.

Satellite telemetry has been used extensively to record the behaviour and distribution of marine turtles, often with a focus on post-nesting migration pathways (Stoneburner 1982; Duron-Dufrenne 1987; Godley *et al.* 2008). Satellite transmitters have generally been deployed on nesting turtles late in the season to reduce the risk of loss/failure during mating, nesting and inter-nesting. As a result, the inter-nesting period is often not captured (Godley *et al.* 2002; Hays *et al.* 2007; Godley *et al.* 2008), although inter-nesting movements have occasionally

been recorded inadvertently when turtles have nested after transmitter deployment (e.g. Blumenthal *et al.* 2006; Whiting *et al.* 2007).

Unlike post-nesting migratory pathways, which can cover several hundreds and even thousands of kilometres (e.g. Cheng 2000; Blumenthal *et al.* 2006), inter-nesting areas are much more localised (Pendoley 2005). Determining the extent of inter-nesting areas via satellite telemetry therefore requires the ability to distinguish fine-scale movements.

While the Argos satellite system has revolutionised the ability to track animal movements, location accuracies are highly variable. The highest accuracy Argos locations (Location Classes 3, 2 and 1) vary in accuracy from 250–1500 m (Argos CLS 2008), with some field tests indicating even lower accuracies (Hazel 2009). Such low accuracies are considered by the researchers to be insufficient for tracking the fine-scale inter-nesting movements of marine turtles.

Advances in satellite telemetry have led to the development of Fastloc GPS technology, which allows the acquisition of GPS locations within a very short timeframe. The accuracy of Fastloc GPS locations varies with the number of satellites used to acquire the location. Field tests by the manufacturer indicate that 95% of locations acquired with more than 10 satellites are accurate to 17 m but that effective locations (95% of locations accurate to within 140 m) can be acquired with as few as 5 satellites (Bryant 2007).



Figure 1. Study area.

While Fastloc GPS locations are generally more accurate than Argos locations, they require more battery power to obtain (Hazel 2009). When programming satellite transmitters it is therefore necessary to achieve a compromise between the number of attempted GPS location acquisitions and the duration that the transmitter will continue to operate.

The Lacepede Islands, approximately 110 km north of Broome in the Kimberley region of Western Australian (Fig. 1), support one of Western Australia's largest green turtle rookeries and lesser numbers of nesting flatback turtles (Prince 1994; Limpus 2009). Despite the importance of the Lacepede Islands for marine turtle nesting, limited data have been published for the area. The objective of this research was to determine the spatial distributions of inter-nesting green and flatback turtles at the Lacepede Islands. A secondary objective was to determine whether satellite transmitters deployed early in the nesting season would continue to provide data throughout the inter-nesting period or would malfunction partway through the inter-nesting period.

Methods

Transmitter attachment

Twenty F4G-291A (Sirtrack Pty Ltd, New Zealand) and two Mk10-AF (Wildlife Computers Inc.) satellite

transmitters were attached to nesting green and flatback turtles at the Lacepede Islands during the 2009–2010 nesting season. All satellite transmitters were deployed from West Island (16°51' S; 122°7' E), the western island of the Lacepede Islands, between 7pm and 2am in December 2009 and February 2010.

Twelve F4G-291A transmitters were attached to 6 green turtles and 6 flatback turtles between 2 and 4 December 2009. The remaining 8 F4G-291A transmitters were attached to 4 green and 4 flatback turtles between 9 and 10 February 2010. The 2 Mk10-AF transmitters were attached to 1 green turtle and 1 flatback turtle on 9 February 2010.

Transmitters were attached to green turtle carapaces according to the methods described by Balazs *et al.* (1996). Green turtles were directed into a large pen (2x2 m) made of plywood for transmitter attachment. Transmitters were attached onto the second central scute using 2-part epoxy resin (Powerfast Pro™) and then coated with antifouling paint (International Longlife). Due to the high humidity, the glue and antifouling paint took about 3.5 hours to dry.

Transmitters were attached to flatback turtles using harnesses as described by Sperling and Guinea (2004). Each harness comprised a moulded polypropylene base-plate, 22 mm wide webbing with Velcro ends and a centralised plastron ring with raised nodules to reduce the potential for snagging (Crackpots Marine and Rural Supplies, Perth). Satellite transmitters were fixed to the base-plate using a fast-curing marine adhesive/sealant and stainless steel screws and coated with antifouling paint (International Longlife) prior to attachment.

Transmitter Settings

Both the F4G-291A and Mk10-AF transmitters provide Argos and Fastloc GPS location data. The Mk10-AF transmitters also provide time-depth data but these data are not presented here.

Transmitter duty cycles were selected to provide a balance between Argos and GPS data. The F4G-291A transmitters were programmed to be switched on continuously for the first 90 days, after which the duty cycle switched to 12 hours on then 72 hours off. GPS location acquisition was attempted every hour and Argos location acquisition was attempted every 40 seconds when the tags were switched on. The Mk10-AF transmitters were programmed to be switched on continuously during February (deployment month) and every third day during all other months. GPS location acquisition was attempted every 20 minutes and Argos location acquisition was attempted every 45 seconds when the tags were switched on.

Data filtering

Location and time data were obtained from the Argos satellite system (<http://www.argos-inc.com>). Although both Argos and GPS data were collected, only GPS data were included in the analyses. GPS data for the F4G-291A and Mk10-AF transmitters were processed with Sirtrack Fastloc Admin Tool Version 1.1.5.8 (Sirtrack Pty Ltd) transmitters and Wildlife Computers Data Analysis Program Version 2.0 (Wildlife Computers Inc.), respectively. Data were filtered to include only those

locations obtained from five or more satellites. One location (for turtle G6) was also removed as it would have required the turtle to swim >5km/h (Luschi *et al.* 1998).

The end of inter-nesting for each turtle was determined from their last potential nesting event for the season, which was defined as a location within 140 m of a sandy beach followed by a period of >30 days without being recorded within 140 m of a sandy beach. The distance of 140 m was based on 95% of locations obtained with 5 satellites being within 140 m of the actual location (Bryant 2007). Although this may have lead to some locations acquired with more than 5 satellites being mistakenly identified as potential nesting events, it was assumed that turtles would commence their post-nesting migrations and leave the inter-nesting area relatively quickly after completing their nesting season (Dodd and Byles 2003; Kennett *et al.* 2004).

Data analyses

Inter-nesting data were plotted in ArcGIS to show the inter-nesting distribution for green and flatback turtles and to calculate the maximum distance each turtle travelled from the site of transmitter attachment. Density histograms with a kernel density estimation of the probability density function of transmissions were generated for both green and flatback turtles, to show the density of transmissions within distance categories from the deployment location. Boxplots were also prepared to examine the variation in distance from the deployment location for green and flatback turtles. Locations that were greater than 1.5 x the inter-quartile range were plotted as outliers.

Study limitations and assumptions

Location data are only acquired when the transmitter aerials break the sea surface. The distribution data therefore only represent the locations of turtles at the sea surface. Substantially more transmissions per day were

received for green turtles than for flatback turtles. As this was a consistent pattern throughout all tracked turtles, it may be attributable to behavioural differences between green and flatback turtles. (e.g. green turtles spend more time at the sea surface than flatback turtles).

It is not known whether the turtles tracked in this study had nested in the weeks or months prior to transmitter attachment, therefore the distribution data may cover only a portion of the inter-nesting period. We have assumed that turtle inter-nesting movements are uniform throughout the inter-nesting period.

Results

Transmitter success and numbers of transmissions received

Of the 22 turtles tagged with satellite transmitters, inter-nesting data were received for 10 green and 5 flatback turtles (Table 1). For 3 of the remaining 7 turtles the GPS function of the transmitters failed, while 1 green and 3 flatback turtles commenced their post-nesting migration immediately after the transmitter was attached.

Green and flatback turtles remained in the inter-nesting area for 20–83 days and 21–40 days after transmitter attachment, respectively (Table 1). All green turtles had left their inter-nesting area and commenced their post-nesting migration by 4/05/2010, indicating that the green turtle nesting at the Lacepede Island occurs from at least December–May, whereas all flatback turtles commenced their post-nesting migration by 12/01/2010 indicating possibly a much shorter nesting season (Table 1). Numbers of transmissions used in the analyses (after data filtering) ranged from 45–599 for green turtles and from 12–142 for flatback turtles. The mean number of transmissions received each day ranged from 1.07–7.22 for green turtles and 0.30–4.18 for flatback turtles (Table 1).

Table 1

Summary of inter-nesting data from satellite transmitters attached to green and flatback turtles nesting at the Lacepede Islands (G=Green turtle; F=Flatback turtle).

Turtle ID	Transmitter model	Release date	Date of last potential nesting event	Days in inter-nesting area after release	Number of data points used in analyses	Mean no. of locations received each day	Maximum distance travelled from nesting beach (km)
G1	F4G-291A	2/12/2009	13/01/2010	42	45	1.07	1.69
G2	F4G-291A	2/12/2009	18/01/2010	47	266	5.66	7.25
G3	F4G-291A	3/12/2009	11/01/2010	39	182	4.67	3.35
G4	F4G-291A	3/12/2009	8/01/2010	36	162	4.50	8.14
G5	F4G-291A	4/12/2009	5/02/2010	63	273	4.33	9.45
G6	F4G-291A	4/12/2009	16/02/2010	74	383	5.18	9.29
G7	Mk10-AF	9/02/2010	1/03/2010	20	114	5.70	7.16
G8	F4G-291A	9/02/2010	15/03/2010	34	219	6.44	24.29
G9	F4G-291A	10/02/2010	14/03/2010	32	115	3.59	9.81
G10	F4G-291A	10/02/2010	4/05/2010	83	599	7.22	47.45
F2	F4G-291A	2/12/2009	5/01/2010	34	142	4.18	40.32
F3	F4G-291A	3/12/2009	12/01/2010	40	12	0.30	26.13
F4	F4G-291A	4/12/2009	2/01/2010	29	117	4.03	43.40
F5	F4G-291A	4/12/2009	25/12/2009	21	80	3.81	48.28
F6	F4G-291A	4/12/2009	5/01/2010	32	104	3.25	37.34

Spatial distribution and extent of inter-nesting habitat

Flatback turtles showed a broader spatial distribution than green turtles during inter-nesting, particularly to the north-east and south-west of the Lacepede Islands (Fig. 2). All five flatback turtles travelled at least 26 km from the nesting beach, whereas only 2 green turtles travelled further than 10 km from the nesting beach during inter-nesting (Table 1). Both species travelled to within 5 km of the mainland of Western Australia, although more transmissions were received near the mainland for flatback turtles than for green turtles (Fig. 2).

The distribution data were positively skewed for both green and flatback turtles (Fig. 3). For green turtles the median distribution from the deployment location was 1.84 km (Fig. 3). Excluding outliers, all green turtle transmissions were within 7.65 km of the deployment location (Fig. 3). The median distribution from the deployment location for flatback turtles was 12.51 km, with all transmissions within 48.28 km of the deployment location (Fig. 3).

The majority of transmissions for green turtles were within 10 km of the deployment location with the highest density of transmissions recorded within 1 km of the deployment location (Fig. 4). Transmissions for flatback turtles were much more broadly distributed (Fig. 4). The highest proportions of flatback turtle transmissions were within 0–4 km of the deployment location with the remaining transmissions relatively evenly distributed out to 48 km from deployment location (Fig. 4).

Discussion

Green and flatback turtle inter-nesting distributions

Prior to this study there were no peer-reviewed studies on the inter-nesting distributions of flatback turtles in Western Australia and only limited studies on inter-nesting distributions of green turtles in Western Australia (*i.e.* Pendoley 2005). Satellite tracking studies based on Argos location data indicate that green turtles from Barrow Island ($n=8$) and Sandy Island ($n=3$) in Western Australia remain within approximately 7 km of their nesting beach during the inter-nesting period (Pendoley 2005). Similarly, the present study found that green turtles generally remained within 10 km but that some turtles occasionally travelled up to 47 km from their nesting beach.

Non peer-reviewed satellite tracking studies using Fastloc GPS location data have shown that inter-nesting flatback turtles from Ashburton Island ($n=6$) and Barrow Island ($n=6$) in Western Australia travel up to 35 km and 70 km from their nesting beach, respectively. Flatback turtles from both islands travelled to the coastal waters adjacent to the Western Australian mainland between nesting events (Chevron Australia 2009; RPS 2010). Similarly, Sperling (2007) demonstrated that flatback turtles from Curtis Island in Queensland ($n=3$) and Bare Sand Island in the Northern Territory ($n=4$) travelled up to 30 km from their respective nesting beaches during inter-nesting, using Argos location data.

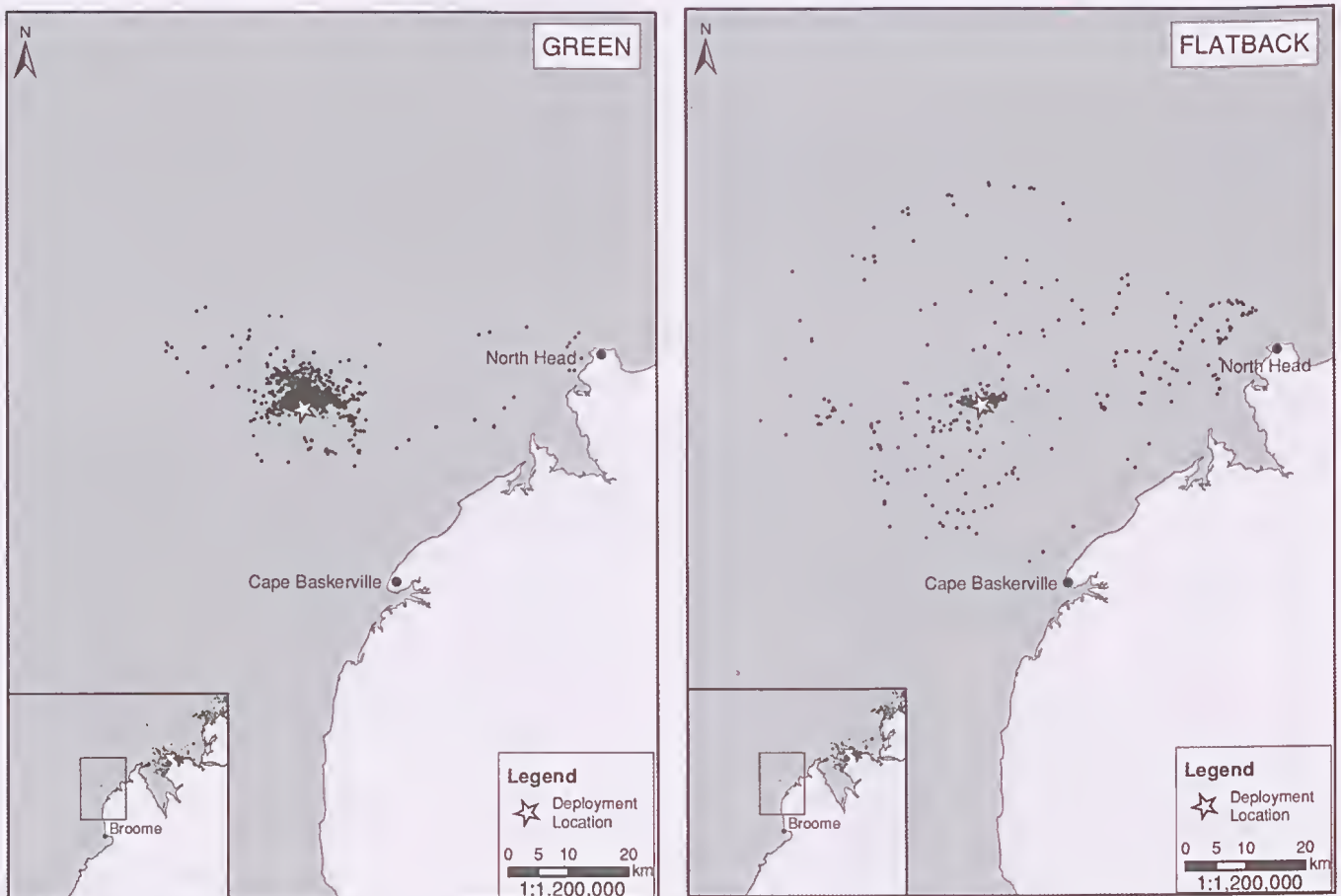


Figure 2. Spatial distribution of GPS (≥ 5 satellites) locations for green and flatback turtles.

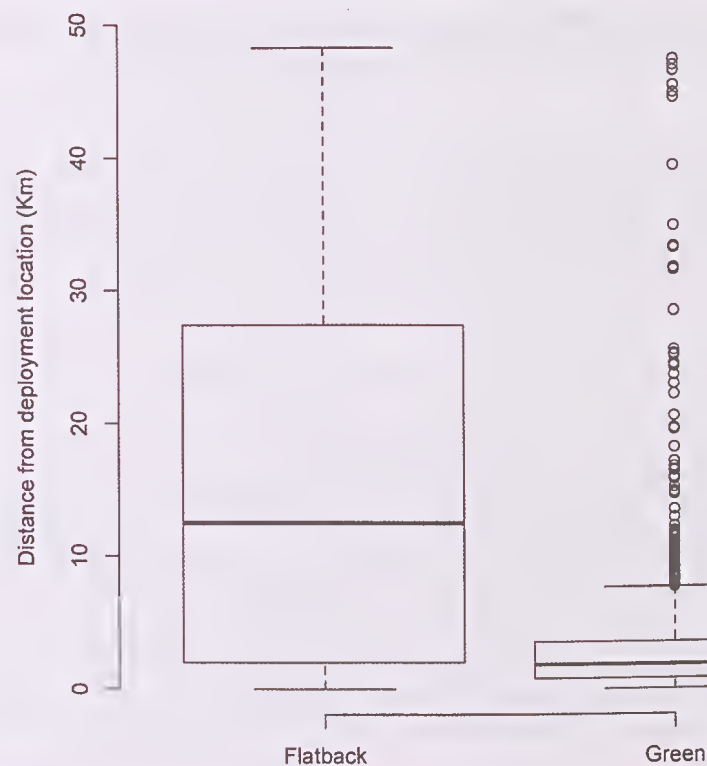


Figure 3. Boxplot of distances from the deployment location for green ($n=2358$ transmissions) and flatback turtles ($n=455$ transmission) during the inter-nesting period. Bottom whisker represents 0-25% of data; box represents 25-75% of data; dark line represents median; top whisker represents 75-100% of data; outliers (*i.e.* transmissions outside $1.5 \times$ the inter-quartile range) are represented by circles.

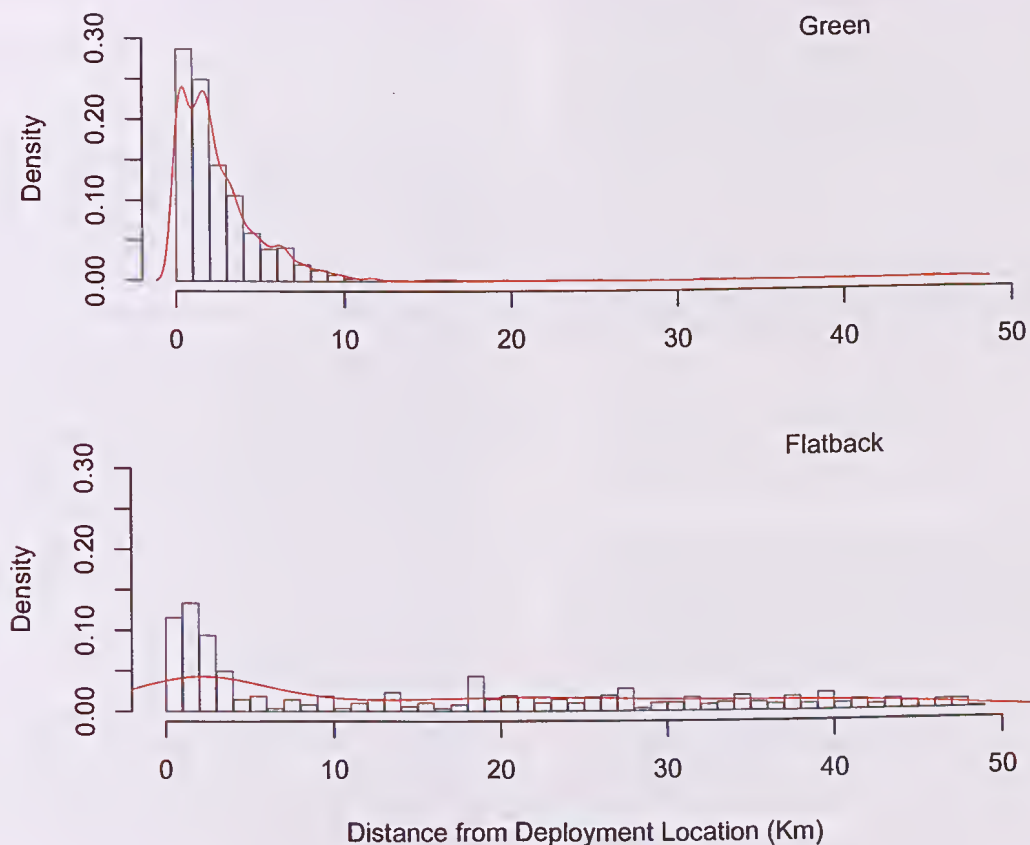


Figure 4. Density histogram (bars) with a kernel density estimation of the probability density function (line) of transmissions at various distances from the deployment location for green ($n=2358$ transmissions) and flatback turtles ($n=455$ transmissions) during the inter-nesting period.

Flatback turtles in the present study travelled at least 26 km and up to 48 km from their nesting beach during inter-nesting, which is consistent with the aforementioned studies.

Although only a very small proportion of Western Australia's inter-nesting green and flatback turtles have been tracked using satellite telemetry, there appears to be a general trend for green turtles to remain within 10 km of their nesting beach and for flatback turtles to travel at least 26 km from their nesting beach during inter-nesting.

Deployment of transmitters early in the nesting season

This study has shown that transmitters can successfully be deployed on nesting turtles early in the nesting season without significant data loss from damaged transmitters that fail to operate. Inter-nesting data were received for 15 of the 22 deployed transmitters and post-nesting migration data were received for 19 of the 22 turtles. Three of the 22 tags failed to provide any Fastloc GPS data and it is possible that the GPS aerials for these transmitters were damaged as a result of mating, nesting or inter-nesting behaviours. However, all three of these transmitters continued to provide Argos location data (not presented here), which is suitable for tracking the post-nesting migratory movements of marine turtles (Hays *et al.* 1999).

Further research avenues

Fastloc GPS technology allows for monitoring of the fine-scale movements of turtles during the inter-nesting period. While data analyses for this study were limited to spatial distribution, further analysis of the numbers of haul-out events (*i.e.* nesting events and false crawls) and re-nesting intervals could be undertaken. Time-series modelling of the turtles' movements may also provide a better understanding of patterns in behaviour during the inter-nesting period.

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The status of breeding seabirds and herons at Ashmore Reef, off the Kimberley coast, Australia

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Abstract

Ashmore Reef is situated on the edge of Sahul Shelf, off the Kimberley coast, Australia. Surveys in 2010 indicate the three small islands within Ashmore Reef support approximately 100,000 breeding seabirds of 16 species and four heron species on an annual basis. That such a diversity and abundance of tropical seabirds utilize a total land area of just 55 ha for breeding purposes is exceptional in an international context. In this paper we review population sizes of breeding seabirds and herons at Ashmore Reef. Bayesian change-point models applied to count data spanning a 60 year period demonstrate that populations of breeding seabirds have increased at this location. Large ground-nesting seabirds display positive step changes in population size since the late 1980s whilst populations of shrub-nesting congeners display similar step changes since the late 1990s. We discuss the potential reasons for these abrupt population increases.

Keywords: seabirds, herons, Ashmore Reef, Kimberley, population size

Introduction

Ashmore Reef lies within Australian waters at 12°20'S, 123°0'E, some 630 km north of Broome and 325 km off the Kimberley coast (Fig. 1). The Ashmore Reef National Nature Reserve serves to protect marine ecosystems with high biological diversity (Commonwealth of Australia 2002). Ashmore Reef contains four vegetated islands (West, Middle and East islands and a recently vegetated cay; total land area ~55 ha), and several additional sandbanks that rise above the high water mark (Fig. 2) (Russell *et al.* 1993).

The available terrestrial habitats at Ashmore Reef support a large population of seabirds, including some of the most important seabird rookeries on the Sahul Shelf (Serventy 1952, Milton 2005, Bellio *et al.* 2007). The diversity of seabirds across the three main islands is exceptional in an Australasian context. It has been speculated that this diversity may have arisen because of the isolated nature of this island group, opportunities for both ground and shrub-nesting species on the islands and the proximity of Ashmore Reef to the Indonesian Through Flow – a potentially nutrient rich current linking the Pacific and the Indian Oceans that is active in the vicinity (Commonwealth of Australia 2002; Milton 2005; Potemra 2005; Bellio *et al.* 2007).

Many seabirds at Ashmore Reef are breeding visitors and are thus present in large numbers on a seasonal basis. Large colonies of Sooty Tern *Onychoprion fuscatus*, Crested Tern *Thalasseus bergii*, Common Noddy *Anous stolidus*, Lesser Frigatebird *Fregata ariel* and Brown Booby *Sula leucogaster* breed on East and Middle islands.

Smaller breeding colonies of Wedge-tailed Shearwater *Ardenna pacifica*, Masked Booby *Sula dactylatra*, Red-footed Booby *S. sula*, Great Frigatebird *Fregata minor*, Little Egret *Egretta garzetta*, Eastern Reef Egret *E. sacra* and Black Noddy *Anous minutus* also occur (Australian National Parks and Wildlife Service 1989; Milton 2005). Many of the bird species present in the region are listed under international treaties for migratory birds (JAMBA, CAMBA and ROKAMBA) and breeding seabirds are listed marine species under the *Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth of Australia 2009). Ashmore Reef is recognised as a Ramsar wetland of international significance, with an area of 58,300 ha being designated in 2002 (Ramsar Convention Bureau 2009). Recently, Ashmore Reef has also been designated an Important Bird Area by BirdLife International on the grounds that it supports exceptionally large numbers of migratory and congregatory species (Birds Australia unpubl. data).

History of visitation and exploitation of the avifauna

The history and development of Ashmore Reef has been thoroughly reviewed by Russell (2005). The reef area and associated islands have an extended record of human visitation dating back ~300 years when Ashmore Reef was discovered by Indonesian fishers who originated from Roti Island (Fox 1977; Dwyer 2000). Initially, exploitation of marine resources by Indonesian fishers focussed on aquatic fauna such as fish and molluscs; seabirds were not harvested as they were considered special in aiding sailors to find land (Dwyer 2000). Subsequently, perhaps as more commercially orientated Indonesian fishers such as the Bajau began visiting the islands (Dwyer 2000), breeding seabirds and their eggs were also taken when available (see Serventy

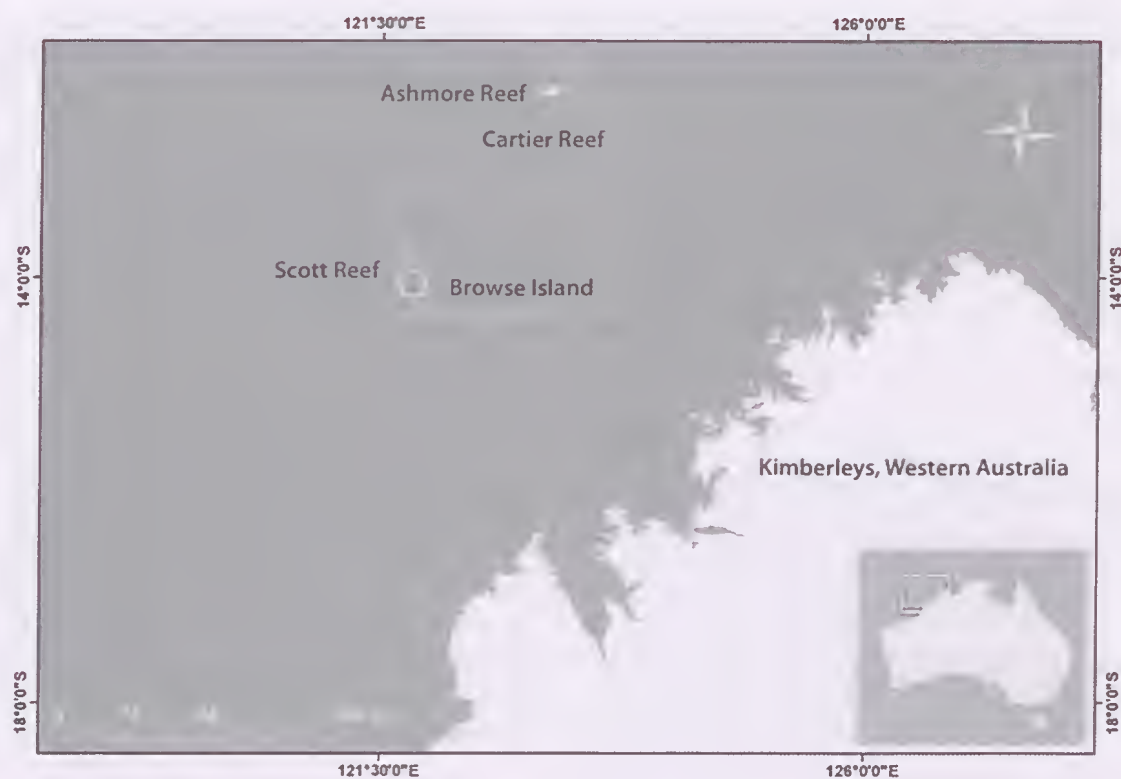


Figure 1. Location of Ashmore Reef, relative to the Kimberley coastline and other Australian reefs and islands in the region. The boxed outline surrounding Ashmore, Cartier and Scott reefs and Browse Island delineates the boundaries of the MOU 74 Box.

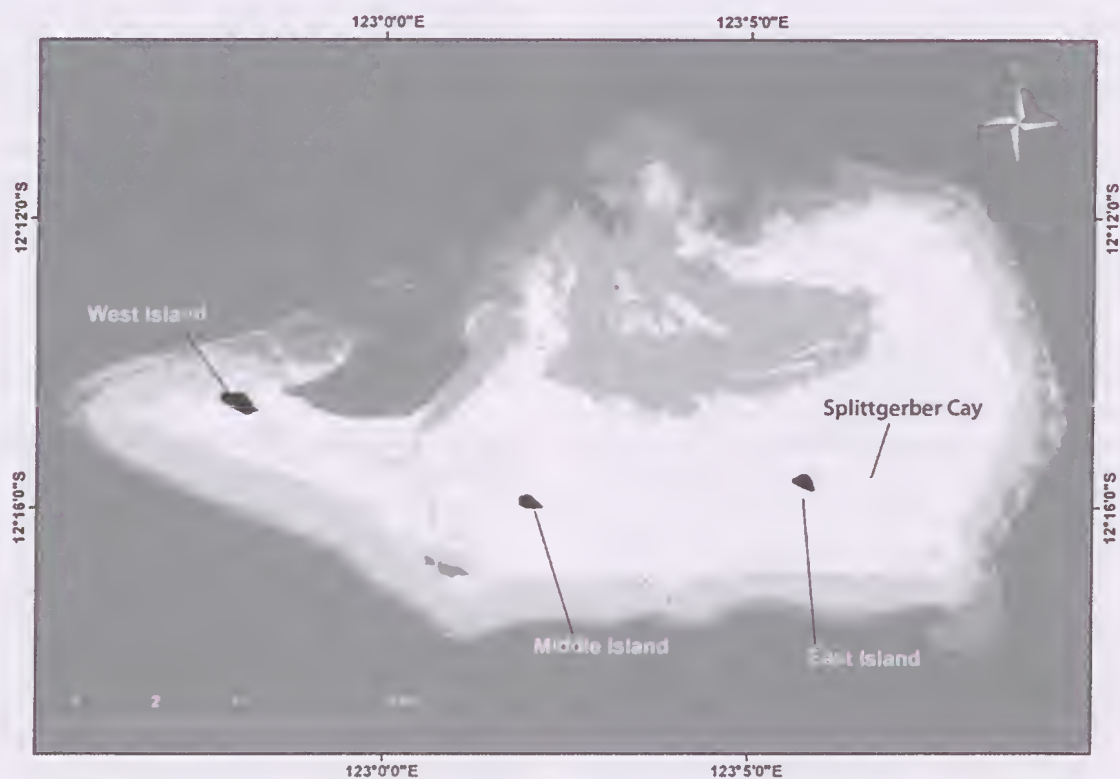


Figure 2. Overview of Ashmore Reef showing the locations and relative sizes of West, Middle and East islands and Splittgerber Cay. Palest shade of grey indicates depths < 4 m, darkest shade of grey indicates depths > 12 m.

1952; Clark 2000; Russell 2005). Ashmore Reef came to the attention of Europeans when Captain Samuel Ashmore chanced upon the area in 1811. Subsequent to this discovery the terrestrial habitats at Ashmore Reef were heavily exploited for guano such that by 1891 all significant phosphate reserves on the islands were exhausted (Woodward 1917; Fairbridge 1948; Langdon 1966; Russell 2005). In addition to disturbance to breeding seabirds by the activity of guano extraction, the presence of phosphate mining camps is also likely to have impacted on breeding seabirds, if for no other reason than adults and nest contents provided a ready source of protein.

During a visit by a CSIRO fisheries vessel in October 1949, Serventy (1952) gathered the first quantifiable data relating to the birds at Ashmore Reef. The expedition also reported some 30 Indonesian *perahu* (traditional fishing vessels) with a complement of ~300 men within the reef area. On that same visit the remains of birds killed by visiting Indonesian fishers were observed on all three islands. The 'take' was implied to be high with 'a small heap of remains of immature boobies' on West Island, a 'few remains of killed birds' on Middle Island and 'quantities of remains of birds killed by visiting fishermen' on East Island (Serventy 1952). Subsequent visits by naval vessels also reported numbers of *perahu* at the reef (Russell 2005) and in July 1974 the HMAS Diamantina reported Indonesian fishers cooking and drying seabirds on the islands (Australian National Parks and Wildlife Service 1989).

In 1974, a Memorandum of Understanding was signed by the Australian and Indonesian governments. Known as the 'MOU 74 Box', the area under the agreement incorporates Ashmore Reef and extends as far south as Browse Island and Scott Reefs (Fig. 1) (Australian National Parks and Wildlife Service 1989). Within the MOU 74 Box certain traditional fishing practices by Indonesian fishers were allowed to continue, but others, such as the harvesting of seabirds and marine turtles, were no longer permitted. Despite this agreement there remained heavy exploitation of resources at Ashmore Reef, including evidence of ongoing (now illegal) take of seabirds. For example, McKean (1980) reported the wings and skins of many Lesser Frigatebirds and Brown Boobies found at several Indonesian camps on West Island in November 1979. In an effort to control this, the then Australian National Parks and Wildlife Service established the Ashmore Reef National Nature Reserve in 1983. Soon after, in 1985, the then Department of Territories commenced a seasonal surveillance program at the reef to prevent the taking of seabirds and turtles. The program involved the presence of a contract surveillance officer during the traditional fishing season (March to November) of each year. This program, with improvements during 1987–88, met with considerable success (Russell 2005). Nevertheless, some illicit activities continued and in 1988 the Australian Government introduced new regulations banning all traditional fishing activities within the boundaries of the reserve (subsistence fishing in a narrow easement near West Island is still permitted). These regulations also prevent any landings by fishers or others on East and Middle islands (Commonwealth of Australia 2002). With the advent of suspected illegal immigrant vessels arriving at

Ashmore Reef (the first vessel arrived in March 1995 (Clark 2000)), a year-round presence by Customs officers (who also act in a reserve warden capacity) aboard dedicated vessel(s) has further improved the protection of biodiversity assets within the reserve (R. Clarke pers. obs.).

Given the changing fortunes of seabirds at Ashmore Reef stemming from both enhanced legislative protection and a history of increasing on-ground enforcement, here we seek to provide a review of current population sizes of breeding seabirds within the reserve. Further, we seek to compare the current population estimates with historical data and discuss the implications of any observed population changes.

Methods

Collation, analysis and review of existing data

Counts of seabirds at Ashmore Reef date back to 1949 when Serventy visited the islands and documented the breeding species present (Serventy 1952). Thirty years passed before McKean (1980) visited in November 1979 and provided the next available summary of seabird numbers present within the reef. This visit marked the start of a period during which the avifauna of Ashmore Reef received considerable attention. In the following 19 years, counts of varying extent were documented on 68 occasions. These counts were principally undertaken by staff from the Australian National Parks and Wildlife Service (now the Federal Department of Sustainability, Environment, Water, Population and Communities (DSEWPC)) but observations by other visitors were also collated. These visits occurred in all calendar months, with at least two visits taking place in any year. A summary of these data has been presented by Milton (2005). Since 1996 (to October 2010) the authors have collectively visited Ashmore Reef on a further 15 occasions, with visits being made in all years since 2000, principally in October and November (10 visits) and January and February (three visits). Bellio *et al.* (2007) report on an additional visit (November 2004), when efforts were made to quantify seabird populations in relation to potential impacts by tropical fire ants *Solenopsis geminata*.

Counts of seabirds during the period 1979 to 1998 were of variable intensity and they were not all conducted by experienced observers (Milton 2005). Further, data held by the authors for this period (Commonwealth of Australia unpubl. data) does not quantify effort beyond specifying the island and the month and year of the visit (*i.e.* total time ashore and whether a count was complete or partial is not specified). In contrast, observations during visits by Milton (1999, 2005); Bellio *et al.* (2007) and the authors (Swann 2005a, 2005b, 2005c, this study) incorporate measures of effort. The methods employed by the authors to record birds have remained largely consistent between visits, with all species encountered being individually counted or, in the case of larger aggregations of seabirds, estimated. Importantly, all of these surveys have involved one or more experienced observers competent in the identification of seabirds in northern Australia and experienced in counting large aggregations of birds.

Potential limitations within the existing data are that visits were principally in October and November of each year (and to a lesser extent in January and February); that counts for some species were incomplete, dependent on the level of island access achieved; and that not all islands at Ashmore Reef were visited on every expedition.

In response to the Montara Well release (see discussion), a targeted field survey began in April 2010 to count seabirds present on the islands and sandbanks of Ashmore Reef in a rigorous and repeatable manner. Complete island-wide counts of seabirds were systematic with the observer recording the number of adults and the number of active nests for all species that were encountered. Active nests provide a more objective measure of seabird colony size (number of breeding pairs) than do counts of adults, as presence by one or both adults at a colony is dependent on breeding stage and time of day. Nevertheless, counts of adults provide the only option, when counts of nests are unachievable. For most species two separate counts were made – all active nests and all adults present (Great Frigatebird, Brown Booby, Red-footed Booby, Masked Booby, Crested Tern and Lesser Noddy *Anous tenuirostris*). In contrast, Sooty Tern, Bridled Tern *Onychoprion anaethetus*, Common Noddy and Black Noddy were nesting amongst herbaceous vegetation and in aggregations that precluded counts of individual nests. As many individuals of the above species, as well as Lesser Frigatebird, were yet to lay eggs and individual nests were not discernible a count of all adults¹ of each species was made. Each island was visited on at least three separate dates during the April 2010 surveys. For the three booby species, Great Frigatebirds and the less abundant tern species (e.g. Bridled Terns) single counts of nests and adults were made during each visit. For abundant species, or species that occur at very high local densities (e.g. Crested Terns) multiple counts by at least two observers were undertaken to ensure a degree of consistency in the final estimate of the maximum number present. Repeat counts were no longer considered necessary when ideal counts (e.g. birds not flushed by aircraft, no interruptions due to rain squalls) did not differ by more than 5%.

As some species of seabird are obligate ground-nesting species (e.g. Brown Booby, Masked Booby, Lesser Frigatebird), whilst others require elevated structures such as shrubs and trees (e.g. Red-footed Booby and Greater Frigatebird) we also provide an overview of recent vegetation changes at Ashmore Reef.

Statistical Analyses

Bayesian change-point models, using free-knot piecewise linear splines (Thomson *et al.* 2010), were applied to data for the large breeding seabirds that occupy Ashmore Reef to characterize temporal trends and objectively identify abrupt changes in these trends.

The basic model for response variable y (e.g. counts of species x) at time t is expressed as:

$$y_t = \alpha_t + f(t) + \varepsilon_t, \quad \text{equation (1)}$$

where, α_t is a time-dependent intercept, $f(t)$ is a continuous function of time, and ε_t is an error term with first order autocorrelation structure (see Thomson *et al.* 2010).

The time-dependent intercept allows for abrupt changes in y at some point in time, or step changes. Step changes are modelled as:

$$\alpha_t = \alpha_1 + \sum_{j=1}^{k_a} \chi_j I(t \geq \delta_j), \quad \text{equation (2)}$$

where α_1 is the species count at time zero (earliest count), k_a is the number of step changes, δ_j is the timing of the j^{th} step change, and χ_j is the value of the change. $I(t \geq \delta_j)$ is an indicator function that equals 1 when $t \geq \delta_j$ and is 0 otherwise.

The temporal trend, $f_t(t)$, is modelled as a piecewise linear regression with an unknown number k_θ of changes in slope, or trend changes, and a corresponding set of times θ_j of trend changes:

$$f_t(t) = \beta_1 t + \sum_{j=1}^{k_\theta} \beta_{[j+1]}(t - \theta_j)_+, \quad \text{equation (3)}$$

where the term $(t - \theta_j)_+$ equals $I(t \geq \theta_j)(t - \theta_j)$.

Given a particular intercept, the term is a piecewise linear and continuous function of time, but when the intercept α_t varies, the combination $\alpha_t + f_t(t)$ is a discontinuous piecewise linear model.

In this model there are four key parameters that determine the number, k_a and k_θ , and timing, δ_j and θ_j of change-points. Using a Bayesian framework with reversible jump Markov chain Monte Carlo sampling (MCMC, Lunn *et al.* 2006; 2009) we evaluated, via likelihood functions, the relative evidence in the data for all possible models, or combinations of change-points. The relative support for each model is expressed as a posterior model probability. The range of models considered possible is specified in the prior distributions for these parameters. Given no prior information or expectations, very vague priors can be used that essentially let the data determine the most likely values of each parameter, although hyper-parameters must still be set which determine the penalty for complexity (and therefore the degree of smoothness in the fitted trend). The resulting posterior distributions allow for probabilistic inferences about the occurrence of change-points in particular years, accounting for uncertainties in both data and other model parameters (including magnitudes and timing of other change-points).

Bayesian models were applied to the suite of large breeding seabirds (frigatebirds and boobies) that occur at Ashmore Reef as it is these species for which human depredation has been most frequently reported (e.g. Serventy 1952; McKean 1980; Australian National Parks and Wildlife Service 1989). As seabird numbers at Ashmore Reef vary considerably throughout the year

¹ As many seabirds are difficult to accurately age once they have left the nest adults are defined here as all free-flying individuals

(this study), and existing count data is biased towards certain seasons, only count data collected in the period September to November of any year was incorporated in analyses. Data were excluded in situations where only one island had been counted within a calendar month. Remaining counts for each species were summed across all three islands. To account for situations where only two of the three islands were counted, a term was included in the model for the number of islands surveyed. This approach accounted for the inevitably lower counts when only two islands were surveyed (c.f. all three). Trends modelled are therefore the expected total count for each species across all islands at Ashmore Reef.

Results

Terrestrial environments

The vegetation at Ashmore Reef has been well documented by Pike & Leach (1997). As one would anticipate for isolated island environments, vegetation communities are simplified. On West Island there is a single dominant shrub species, *Argusia argentea*, two Coconut Palms, several other shrubs represented by very small numbers of individuals and a range of creepers, annual herbs and grasses (Pike & Leach 1997; April 2010, this study). In October 2010 there were two living *Argusia argentea* shrubs less than 80 cm in height on Middle Island and no apparent shrubs on East Island (this study). All other vegetation on these two islands is characterised by ground creepers, annual herbs and grasses. The current vegetation on East and Middle islands reflects considerable change since the publication of Pike & Leach (1997). All three Coconut Palms on

Middle Island have died, with a single dead stem remaining near the now abandoned well. Similarly, shrubs reported by Pike & Leach (1997) that occurred on Middle and East Island have also since died. The dead remnants of *Scaevola taccada* shrubs now serve as the principal nesting sites for both Red-footed Boobies and Great Frigatebirds on Middle Island.

A sandbank to the east of East Island is now vegetated (first noted October 2009, this study). Three grass species were present on Splittgerber Cay in April 2010, when the total vegetated area was measured at 1150 m². Whilst there is some evidence that both Brown Booby and Eastern Reef Egret have started nesting on this cay this change is so recent (first evidence of nesting observed in October 2010) as to have no bearing on existing count data (R. Clarke unpubl. data).

The total land area of the three main islands at Ashmore Reef has been previously reported, yet there appears to be considerable variation in the literature as to the actual size of each (e.g. Carter 2003; Bellio *et al.* 2007; Clarke *et al.* 2009). As these islands may be somewhat dynamic, reported variation in part may reflect changes following disturbance and deposition events (e.g. cyclones), however it also seems likely that some of the observed variation is due to inaccurate or 'casual' estimates of total land area. During April 2010 the land area for each island was measured at the high tide line, using a GPS unit. West Island had a total land area of 28.1 ha, Middle Island had a total land area of 13.0 ha and East Island had a total land area of 13.4 ha.

Breeding seabirds

Sixteen species of seabird and four species of heron have been reported to breed at Ashmore Reef. The

Table 1

Recent (post-1990) breeding distribution of seabirds and herons on the three main islands of Ashmore Reef, Australia. 'Not observed' indicates *breeding activity* has not been reported, but adults of these species may still have been observed ashore at times. Question marks indicate some level of uncertainty.

Species	West Island	Middle Island	East Island
Wedge-tailed Shearwater	Regular	Not observed	Not observed
Red-tailed Tropicbird	Regular	Occasional?	Occasional?
White-tailed Tropicbird ¹	Regular	Occasional	Occasional?
Masked Booby	Not observed	Regular	Regular
Red-footed Booby	Not observed ²	Regular	Regular
Brown Booby	Not observed	Regular	Regular
Great Frigatebird	Not observed ²	Regular	Occasional?
Lesser Frigatebird	Not observed	Regular	Regular
Crested Tern	Occasional	Regular	Regular
Lesser Crested Tern	Not observed	Unconfirmed	Unconfirmed
Roseate Tern	Not observed	Occasional	Occasional
Bridled Tern	Not observed	Regular	Regular
Sooty Tern	Not observed	Regular	Regular
Common Noddy	Not observed	Regular	Regular
Black Noddy	Not observed	Regular	Regular
Lesser Noddy	Not observed	Regular?	Regular?
Eastern Great Egret	Not observed	Occasional?	Not observed
Little Egret	Occasional	Occasional?	Occasional?
Eastern Reef Egret	Regular	Regular	Regular
Nankeen Night-Heron	Occasional	Not observed	Not observed

¹ Latin names are presented in the text except for White-tailed Tropicbird *Phaethon lepturus* Lesser Crested Tern *Thalasseus bengalensis*, Roseate Tern *Sterna dougallii*, Nankeen Night Heron *Nycticorax caledonicus* and Eastern Great Egret *Ardea modesta*.

² Has roosted on West Island on occasion (e.g. Oct 2010) and may be prospecting.

highest diversities and greatest densities of breeding seabirds and herons are found on Middle Island (14–17 breeding species per year) and East Island (12–16 breeding species per year) with West Island hosting the largest colony of Eastern Reef Egret, the only colony of Wedge-tailed Shearwaters and most of the breeding tropicbirds (Table 1). The seabirds present at Ashmore Reef display a variety of reproductive strategies (Fig. 3). Most species breed annually, several species breed biannually and a small number of species have been reported to breed at Ashmore Reef sporadically (Table 1). Most seabirds at Ashmore Reef breed through the tropical dry season (May to November), with the majority of species commencing egg laying and incubation in April. These include Lesser Frigatebird, three species of noddy and Brown Booby. Red-footed and Masked Boobies also breed through the dry season, however specific months for egg laying are less well defined and documented. Several other species display a more variable response to season. For example, Crested and Sooty Terns have been reported to commence laying at various times including the months of January, April and November. In contrast Wedge-tailed Shearwaters appear to be the only obligate wet season breeder, though available data indicates both species of tropicbirds are also most abundant between the months of January and April. Eastern Reef Egrets, which are the only abundant heron species present within the reserve system, have been reported breeding in most months (Fig. 3).

Counts conducted in April 2010 occurred when the majority of dry season breeding species were present and many of these had commenced incubation. Thirteen of the 16 breeding seabirds at Ashmore Reef were attending active nests at this time, though no herons or egrets were

observed breeding (Tables 2–4). As all seabirds on both East and Middle islands were counted over consecutive days and because most species were attending nests it is considered appropriate to pool these data to provide total measures of abundance. Approximately 72,000 breeding seabirds were utilizing islands on Ashmore Reef at the time of the April 2010 survey. Notable counts included 44,805 Common Noddies, 4379 Brown Boobies nests (extrapolated to 8758 breeding adults), 5382 Crested Terns and 4277 Lesser Frigatebirds (Tables 3–4). Whilst numbers are not as spectacular, the largest reported colony sizes at Ashmore Reef for Great Frigatebird (40 nests), Red-footed Booby (101 nests), Masked Booby (33 nests) and Red-tailed Tropicbird *Phaethon rubricauda* (17 nests) were also obtained during April 2010. Lesser Noddy was also confirmed as a breeding species at Ashmore Reef with 13 adults and four nests observed.

Change-point analyses

For the purposes of this review, change-point analyses focuses on the five large-bodied seabirds that breed at Ashmore Reef. For the three ground-nesting species (Brown Booby, Masked Booby and Lesser Frigatebird), change-point models identified positive step changes with significant posterior support in the period 1985 through until 2002 (Fig. 4). For the two shrub-nesting species (*i.e.* Red-footed Bobby and Great Frigatebird) similarly applied models identified positive step changes with significant posterior support during the period 1998 to 2003 (Fig. 4).

The ground-nesting Brown Booby is the most abundant of the *Sulidae* at Ashmore Reef, reflecting a remarkable recovery. In October 1949 Serventy (1952)

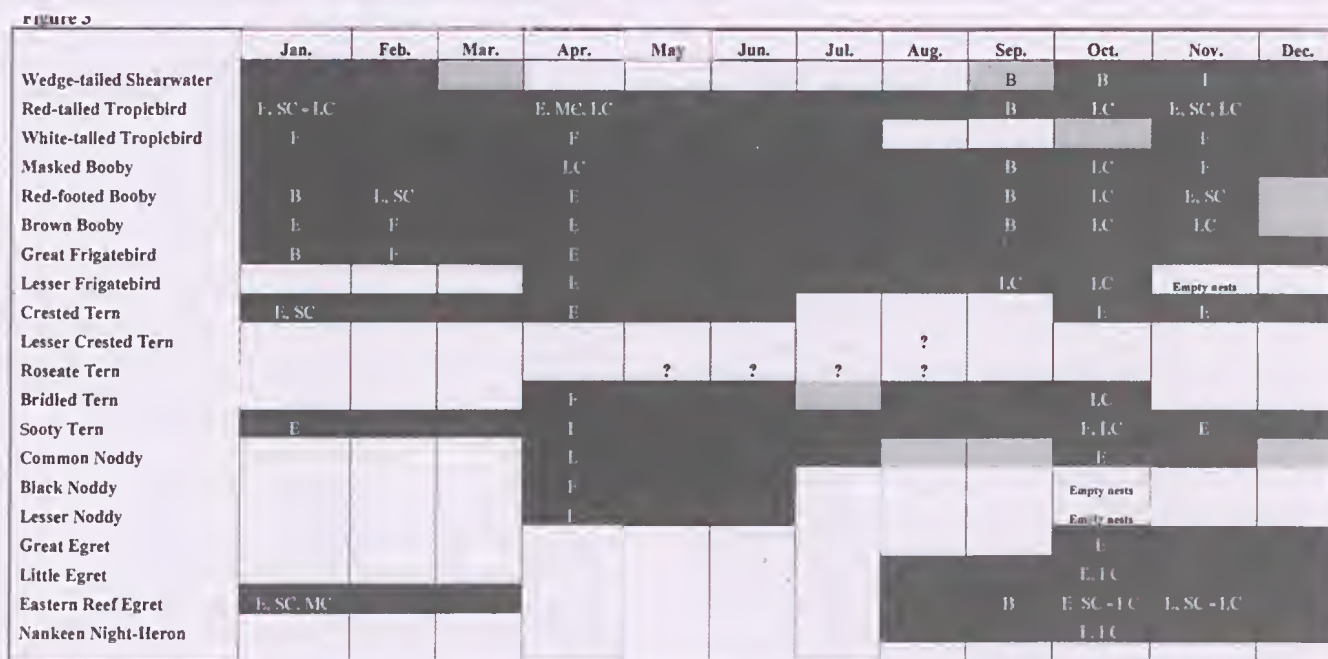


Figure 3. Breeding seasons of seabirds and herons at Ashmore Reef. Breeding months (seabirds) are shaded dark grey, pale grey indicates 'shoulder' months. Letters denote reported reproductive stage; E = eggs; SC = small chick; MC = medium chick; LC = large chick or fledgling; B = breeding reported but the reproductive stage not specified. Data sourced from Milton (2005), Swann (2005a, 2005b, 2005c), Bellio *et al.* (2007) and authors unpubl. data. Known breeding stages extrapolated to breeding seasons using data in Marchant & Higgins (1990a, 1990b), Higgins & Davis (1996). Unshaded cells indicate there is no evidence of breeding, though for many species breeding may still take place in these months.

Table 2

Counts of tropicbirds and Eastern Reef Egrets on West Island, Ashmore Reef. Counts were obtained during 17 visits between October 1998 and October 2010. In instances where several counts were made over consecutive days the highest count from that period is presented. Tropicbird records from Middle and East Islands are presented in Tables 3 and 4.

	Oct- 1998	Oct- 2000	Oct- 2001	Nov- 2001	Jan- 2002	Feb- 2003	Sep- 2003	Oct- 2004	Nov- 2004	Jan- 2005	Oct- 2005	Oct- 2006	Oct- 2007	Oct- 2008	Oct- 2009	Apr - 2010	Oct- 2010
Red-tailed Tropicbird																	
adults	0	4	2	10	8	10	20	4	4	17	12	4	4	10	3	24	8
nests	0	2	1	5	2	4	7	2	3	14	3	3	3	8	1	17	2
White-tailed Tropicbird																	
adults	0	0	0	4	2	4	3	3	0	8	0	3	3	4	1	3	5
nests	0	0	0	2	1	0	0	2	0	2	0	0	0	0	0	1	1
Eastern Reef Egret																	
adults	Not reported	100	300	300	191	150	200	400	–	400	200	500	300	700	400	250	300
active nests?	–	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

Sources: authors unpublished data, Swann (2005a), Swann (2005b), Swann (2005c), Milton (2005), this study

Table 3

Seabird counts at Middle Island, Ashmore Reef. The maximum count of adult seabirds obtained during 48 visits between 1979 and 1998 and counts of adult seabirds during 12 visits between January 2002 and October 2010 are shown. In instances where several counts were made over consecutive days the highest count from that period is presented. Numbers in bold indicate breeding of that species was explicitly reported for that count. All counts refer to adults except Brown Booby in April 2010 (*n* = active nests).

Date	Max. count 1979–1998	Jan 2002	Jan 2003	Sep 2003	Oct 2004	Jan 2005	Oct 2005	Oct 2006	Oct 2007	Oct 2008	Oct 2009	Apr 2010	Oct 2010
Red-tailed Tropicbird	1	0	1	1	1	0	0	2	0	0	0	0	0
White-tailed Tropicbird	6	0	3	0	0	2	0	1	1	1	0	0	1
Masked Booby	3	4	3	2	3	14	10	20	10	20	30	28	1
Red-footed Booby	15	46	42	40	60	220	30	50	80	80	100	101	12
Brown Booby	1050	1530	1250	1000	1000	2300	1000	2000	5000	1000	3000	2841n	940
Great Frigatebird	24	8	4	2	3	20	20	30	20	20	20	65	10
Lesser Frigatebird	1991	1000	300	100	300	300	200	2000	800	300	1000	2504	1160
Crested Tern	400	150	105	300	60	325	70	500	300	10	250	2814	125
Bridled Tern	239	0	0	0	10	0	0	5	8	1	2	50	15
Sooty Tern	40000	15000	5000	50	5000	50	3000	10000	15000	100	500	2500	280
Common Noddy	10000	1500	260	5000	15000	60	200	3000	700	2000	1800	13875	17000
Black Noddy	120	100	3	2	6	0	10	5	5	0	30	180	80
Lesser Noddy	120	0	0	0	0	0	0	0	0	0	1	7	3

Sources: authors unpublished data, Swann (2005a), Swann (2005b), Swann (2005c), Milton (2005), this study

Table 4

Seabird counts at East Island, Ashmore Reef. The maximum count of adult seabirds obtained during 51 visits between 1979 and 1998 and counts of adult seabirds during nine visits between January 2002 and October 2010 are shown. In instances where several counts were made over consecutive days the highest count from that period is presented. Numbers in bold indicate breeding of that species was explicitly reported for that count. All counts refer to adults except Brown Booby in April 2010 (*n* = active nests).

	Max. count 1979–1998	Jan 2002	Jan 2003	Jan 2005	Oct 2005	Oct 2006	Oct 2007	Oct 2009	Apr 2010	Oct 2010
Red-tailed Tropicbird	6	1	1	0	0	0	0	0	0	0
White-tailed Tropicbird	1	0	0	0	2	2	5	0	0	0
Masked Booby	9	5	25	4	10	5	15	8	10	6
Red-footed Booby	0	0	12	8	10	12	40	30	20	10
Brown Booby	500	1800	2000	2200	1000	3000	3000	1900	1538n	850
Great Frigatebird	2	0	4	0	5	2	10	0	0	1
Lesser Frigatebird	140	800	2000	600	300	1000	500	300	1773	470
Crested Tern	2700	310	310	150	10	10	400	85	2568	2
Bridled Tern	2400	0	0	0	3	5	6	5	300	10
Sooty Tern	20000	25000	10000	350	10000	10000	10000	7000	5000	8000
Common Noddy	54000	3000	1800	530	3000	5000	400	1070	30930	3000
Black Noddy	375	1500	5	3	20	10	20	70	450	1
Lesser Noddy	20	0	0	0	0	0	0	0	6	0

Sources: Swann (2005a), Swann (2005b), Swann (2005c), Milton (2005), this study

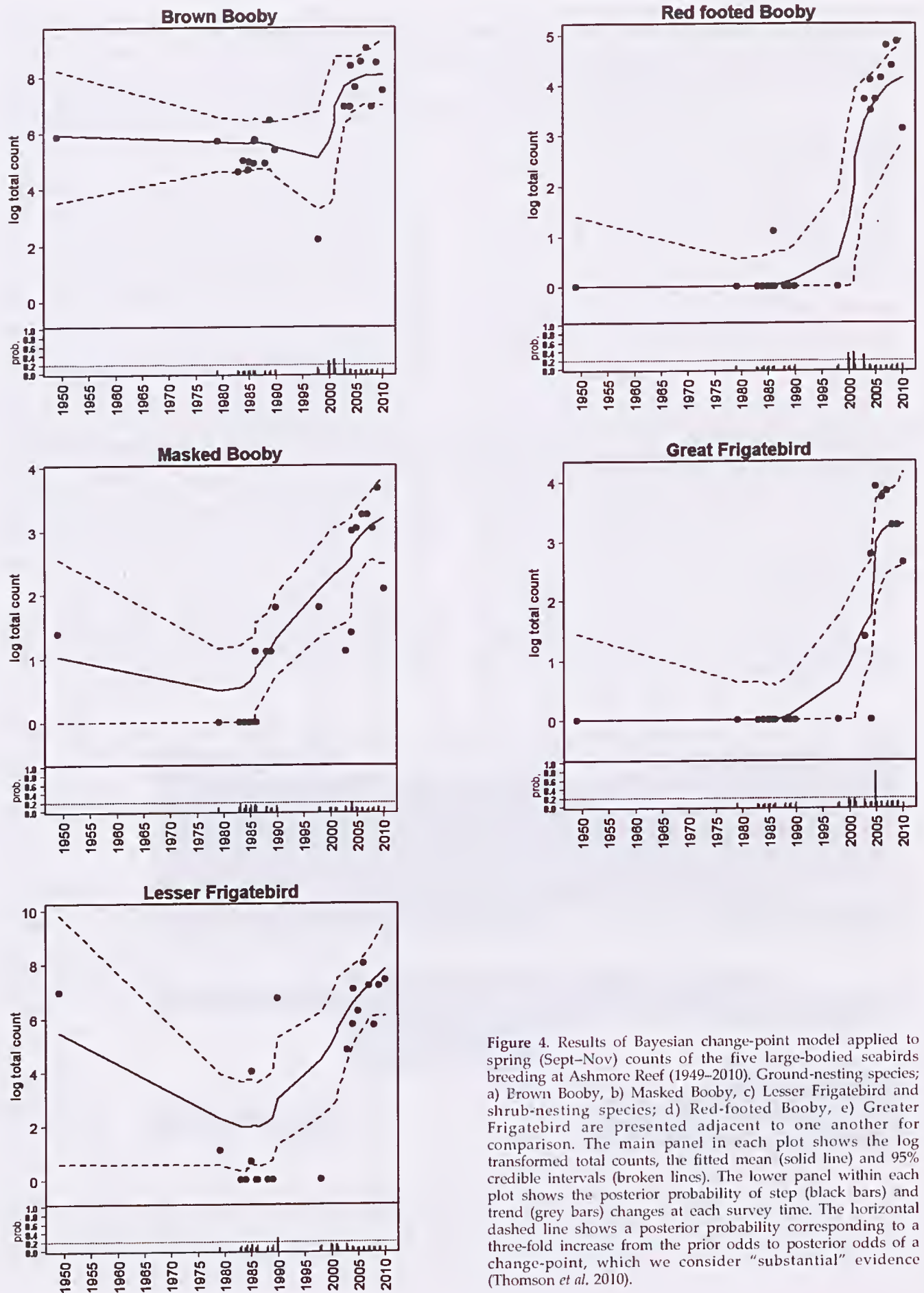


Figure 4. Results of Bayesian change-point model applied to spring (Sept–Nov) counts of the five large-bodied seabirds breeding at Ashmore Reef (1949–2010). Ground-nesting species; a) Brown Booby, b) Masked Booby, c) Lesser Frigatebird and shrub-nesting species; d) Red-footed Booby, e) Greater Frigatebird are presented adjacent to one another for comparison. The main panel in each plot shows the log transformed total counts, the fitted mean (solid line) and 95% credible intervals (broken lines). The lower panel within each plot shows the posterior probability of step (black bars) and trend (grey bars) changes at each survey time. The horizontal dashed line shows a posterior probability corresponding to a three-fold increase from the prior odds to posterior odds of a change-point, which we consider “substantial” evidence (Thomson *et al.* 2010).

reported approximately 40 birds over West Island but no nesting, 200 birds at Middle Island including many free-flying immature birds, and a few adults but no young on East Island. In 1979 McKean reported 300 on East Island but no birds on West or Middle Island (McKean 1980). Between 1983 and 1988 Milton (2005) estimated that between zero and 20 pairs nested there in any year. In the late 1990s, a high count of 1050 on Middle Island in May 1998 and 293 on East Island in the same month was documented (DSEWPC unpubl. data). This upward trend continued through the last decade such that by April 2010 4379 nests (extrapolated to 8758 breeding adults) were counted across Middle and East islands (Tables 3 and 4, Fig. 4).

Small but increasing numbers of the ground nesting Masked Booby breed on Middle and East islands. In October 1949 Serventy (1952) recorded a single adult on East Island and two adults on Middle Island. Between 1983 and 1988 Milton (2005) estimated up to two pairs nested there in any one year. More recent data demonstrates the population has been increasing, with 28 birds counted across Middle and East islands in January 2003 (Tables 3 and 4). The highest count to date was obtained in April 2010 when a total of 38 adults were ashore and 33 active nests were located. After an apparent period of absence (there are no records between 1979 and 1986 despite 44 survey visits to Middle Island and 36 survey visits to East Island during this period; DSEWPC unpubl. data), the species has now successfully recolonised Ashmore Reef (Fig. 4).

The Red-footed Booby is either a recent colonist at Ashmore Reef or it has re-established after a long period of absence. Serventy (1952) reported 'some substantial old nests in a clump of tall bushes' on West Island and suggested they may have belonged to the Red-footed Booby, though he was unable to confirm this and did not observe any individuals. Milton (2005) did not report any Red-footed Boobies nesting within the reserve up to 1988; the first reports of birds ashore were in May 1995 when two individuals were noted on Middle Island (DSEWPC unpubl. data). Since 2000, birds have been present during every documented visit to Middle Island. Subsequently, the species colonised East Island during 2002. The highest count of nests was obtained in April 2010 when a total of 101 active nests were recorded across Middle (91 nests) and East islands (10 nests) (Fig. 4).

Although Serventy (1952) reported that the Lesser Frigatebird was the predominant nesting bird on Middle Island, much of the evidence for breeding was in the form of 'heaps of young birds remains (heads, down and quills)' amongst 442 live young. While McKean (1980) also reported the 'wings and skins of many at several Indonesian camp sites', depredation was such that he detected no breeding activity and observed just two adults in flight during his entire visit. Milton (2005) reported between zero and 750 Lesser Frigatebird pairs bred at Ashmore Reef between 1983 and 1988. Since that time numbers have gradually increased (Fig. 4). By January 2003, 2300 birds were reported to be nesting across both breeding islands (Swann 2005b). More recently in April 2010, 4277 adults were counted across Middle and East islands (Tables 3 and 4, Fig. 4).

On the first occasion that the Great Frigatebird was ever recognised at Ashmore Reef, 24 birds were counted

(Middle Island, May 1995; DSEWPC unpubl. data). Since that time numbers have generally remained stable with regular counts of ~20 in the last five years (Table 3) and a high count of 65 adults and 40 active nests in April 2010 (Tables 3 and 4, Fig. 4).

Discussion

The islands of Ashmore Reef support internationally significant numbers of seabirds (Milton 2005, Bellio *et al.* 2007). Up to 54,000 Common Noddies, 45,000 Sooty Terns, 5000 Brown Boobies and in excess of 4000 Lesser Frigatebirds have been reported to breed on Middle and East Island (Milton 2005, DSEWPC unpubl. data, this study; Tables 3 and 4). Some of these colonies are amongst the largest breeding colonies of that species in the Australasian region. For example Bellio *et al.* (2007) report that Ashmore Reef supports the largest colony of Sooty Terns in Western Australia and the second largest colony of Common Noddy in Australia. Although previous authors have concluded that Ashmore Reef may support up to 50,000 breeding seabirds (Milton 2005; Bellio *et al.* 2007), data presented here demonstrates the total number of breeding seabirds currently approximates 100,000 individuals² during a 12 month cycle. The significance of Ashmore Reef as a site for breeding seabirds is further highlighted by the fact that most seabirds are listed under one or more of the bilateral migratory bird agreements to which the Commonwealth of Australia is a signatory (JAMBA, CAMBA and ROKAMBA). As these bird agreements are incorporated in national environmental legislation all species are also listed under the *EPBC Act 1999* as marine species and/or migratory species (Commonwealth of Australia 2009).

A rigorous monitoring program that commenced in April 2010 is already producing valuable insights into seabird populations at Ashmore Reef. Not only have these counts demonstrated that seabird abundances at Ashmore Reef are larger than previously thought, clarification of the status of individual species is also occurring. For example, questions regarding the identity of Lesser Noddy at Ashmore Reef have previously been raised (Australian National Parks and Wildlife Service 1989; Stokes and Hinchey 1990; Higgins & Davies 1996; Commonwealth of Australia 2002). Observations and photographs of this species carrying nesting material, alighting on newly constructed nest platforms and of a single nest containing an egg confirm the species status as a breeding seabird within the reserve, albeit with a very small population (also Johnstone and Storr 1998).

Sixty years of counts

Despite the remoteness of Ashmore Reef, observations of seabird numbers date back to 1949, with more regular counts taking place since 1979. Although there were extended periods during which no data were collected,

² ~72,000 adult seabirds were counted in April 2010. As this number does not include any adults foraging at sea at the time of the counts, nor many individuals of breeding species that breed at a later date in the year (e.g. Wedge-tailed Shearwater, Roseate Tern) a total seabird population of 100,000 over a 12 month cycle is considered a conservative estimate.

this dataset has proved invaluable to assess the changing fortunes of seabirds at Ashmore Reef. Whilst many species were present and breeding in moderate numbers during 1949 it is apparent that a number of these species were driven to near local extinction due to excessive harvesting in subsequent decades. Although literature implicates traditional fishermen from Indonesia for much of this take (Serventy 1952; McKean 1980; Australian National Parks and Wildlife Service 1989; Russell 2005), there can be little doubt that guano collection prior to the existence of any count data will also have had its impacts.

Following the ratification of the Ashmore Reef Nature Reserve in 1983 the regions seabirds have received increasing protection. This commenced with enforcement patrols soon after the reserve was established (Russell 2005). Increasing levels of surveillance have culminated in a permanent presence by enforcement agencies at Ashmore Reef in recent years and this is reflected in the growth of breeding seabird populations at Ashmore Reef.

For the large breeding species of seabird (*i.e.* boobies and frigatebirds) increased protection following the more permanent presence of staff from border protection agencies and DSEWPC (and its predecessors) has led to marked changes in status. Indeed, positive responses that reflect a stepped change in abundance were detected for all five species subjected to Bayesian change-point modelling. Stepped changes in populations of large ground-nesting seabirds occurred up to a decade earlier than was observed for the two shrub-nesting species. Such a difference most probably reflects the fact that Red-footed Booby and Great Frigatebird had been completely extirpated (assuming both species had bred there in the past) and their initial population increase would be expected to be relatively slow, as at least initially it must have been driven solely by immigration, and not by recruitment from an existing breeding population. As shrub-nesting species, the Great Frigatebird and Red-footed Booby now pose a dilemma for management. Both species will ultimately be limited by the availability of nest sites on East and Middle islands as few shrubs remain there and most of these have died in the past decade. That nest site availability may already be limiting is demonstrated by recent observations of Red-footed Booby nests positioned atypically just 0.2–0.5 m above the ground on compacted herbaceous material (R. Clarke unpubl. data). The construction of a small number of artificial nesting platforms (*e.g.* Fairchild *et al.* 1985, LeCorre 1997, Rauzon & Drigot 1999) may be required to at least maintain the current populations of these two shrub-nesting species.

It is clear that the designation of the reserve and subsequent enforcement has provided opportunities for seabirds to both re-establish and increase markedly at Ashmore Reef. Such a model for protection may also be worth considering for other 'seabird' islands situated within the MOU 74 Box. In particular, Browse Island situated ~150 km off the Kimberley coast (Fig. 1) would be a clear candidate for increased enforcement. It was once regarded as the most famous of the northern Australian guano islands (Serventy 1952), demonstrating that it was once a significant site for breeding seabirds. However, breeding seabirds were extirpated from the island in historic times as Serventy (1952) reported that

"inspection proved a great disappointment as there were no seabirds of any kind, nor any indication that the island had been used as a nesting or roosting place for years". Since that time colonies of Crested Terns have bred there on occasion (*e.g.* Abbott 1979; the authors unpubl. data), but no other seabird species have apparently re-established. That there continues to be a significant presence by Indonesian fishers (*e.g.* 11 *perahus* were anchored in the lee of the island in Nov 2010), and that poaching of turtles continues (R. Clarke pers. obs.), suggests increased enforcement of this reserve may lead to further positive outcomes for breeding seabirds (and turtles) in the region.

Whilst illegal harvesting of seabirds appears now to be largely controlled at Ashmore Reef, other threats to seabirds at this site remain. In particular, the increasing development of the Sahul Shelf for oil and gas extraction (*e.g.* Russell 2005) poses novel threats and challenges for the management of the nature reserve. For example an uncontrolled well release from the Montara H1-ST1 Development Well occurred on 21 August 2009 (Gilbert & King 2010). Situated on the Sahul Shelf 157 km east of the Ashmore Reef National Nature Reserve, the release of gas, condensate and crude oil continued from the well head until the well was successfully intercepted and subsequently plugged on 3 November 2009. By the end of October 2009, evidence of petroleum-based products had been reported at or in the vicinity of Ashmore Reef and small numbers of oiled birds were recovered both at sea and on the islands at Ashmore Reef (*e.g.* Watson *et al.* 2009; Clarke 2010). The extent of the resultant oil slick has been variously reported, with satellite imagery demonstrating that an area of 95,554 km² surrounding the Montara Well showed evidence of hydrocarbon contamination at some time during the spill period (Gilbert & King 2010). The impetus for a rigorous ongoing monitoring program targeting breeding seabirds (and shorebirds) at Ashmore Reef that commenced in April 2010 stemmed from this event (Clarke 2010).

A monitoring program for Ashmore Reef seabirds

As a component of the response to the Montara Well release, biannual monitoring surveys to Ashmore Reef (and other seabird islands in the region) have been instigated.

Two surveys per annum is considered to be the minimum number of visits necessary as:

- Seabird species that breed on Ashmore Reef islands do so at different times of year (Fig. 3)
- Some seabird nesting events may be aseasonal. As such the timing of breeding for these species is difficult to predict. Biannual visits increase the probability of detecting these events and adequately documenting them.
- Biannual monitoring provides opportunity to gather more extensive time-series data on year-round resident breeding species such as the Eastern Reef Egret and Brown Booby.

Milton (2005) identified biannual surveys in the periods April to June and October to December as an appropriate strategy to monitor population trends at Ashmore Reef National Nature Reserve. With the benefit

of additional data, including annual counts for the past decade, optimal survey windows have been further refined. The most optimal period is now considered to span the period from early April to mid-May; with a second survey conducted in November. The former coincides with the maximum number of breeding species present, and covers the incubation period of most species. The second visit provides opportunity to assess several seabird populations that would be inadequately covered in April (e.g. Wedge-tailed Shearwater), count used nests of some species (Lesser Frigatebird and Black Noddy) to provide a second annual assessment of the breeding population, and provide population-wide counts of all seabirds at a comparable time (October–November) to the bulk of existing data collected since 1996 (Milton 1999, 2005; Bellio *et al.* 2007; this study). A November visit also provides opportunity to count the international significant numbers of shorebirds present at Ashmore Reef (Clarke 2010; Rogers *et al.* 2011), not otherwise discussed here.

Future directions and priorities

Past and present research regarding seabirds at Ashmore Reef has focussed on population sizes and breeding phenology of seabirds within the reserve boundaries (e.g. Milton 2005; Bellio *et al.* 2007; this study). Recently seabird research has been further expanded such that annual monitoring will now provide a robust dataset with which to assess inter-annual fluctuations and long-term trends in populations of breeding seabirds at Ashmore Reef. In contrast, a significant knowledge gap exists regarding the at-sea distribution and foraging ranges of seabirds that utilize the reserve as a breeding ground. Such a knowledge gap has management implications given that all species (excluding the breeding herons) are known to forage over marine waters outside of the reserve boundaries on a regular basis (the authors unpubl. data).

With the increasing interest in oil and gas reserves on the Sahul Shelf (Russell 2005), it is imperative that some effort be expended to identify the at-sea distribution of seabirds utilizing Ashmore Reef. In particular areas that provide regular and repeat locations suitable for foraging by seabirds should be identified such that management of marine industries can be better informed.

At present all voyages to and from Ashmore Reef for the purpose of bird surveys employ standard techniques to routinely record at-sea observations of seabirds (the authors unpubl. data). While this provides useful insights into at-sea distribution of seabirds and may potential identify some areas of high productivity visited by breeding seabirds, it is not possible to cover all areas of potential interest on such voyages. A more robust program would involve the deployment of location-reporting technology (geolocators, GPS loggers and satellite tags) on a representative sample of seabird species that utilise the breeding islands. As marine survey data demonstrates even congeneric seabird species (e.g. the three breeding *Sulidae*) forage at different distances from shore, it is recommended that such a program extend to cover a representative range of breeding seabirds from Ashmore Reef. Size differences, known dispersive or migratory capabilities, and breeding seasons would all influence the necessary sample sizes

and the types of technologies to be deployed. Nevertheless, there exist a range of suitable technologies to undertake such work (e.g. Pennycuik *et al.* 1990; Weimerskirch *et al.* 2006; Catry *et al.* 2009; Weimerskirch *et al.* 2009). Such a program would provide managers with a clear understanding of the spatial needs of seabirds that range from Ashmore Reef to feed whilst using the terrestrial environments as a focal point for breeding purposes. It would also help fill the current gap in knowledge regarding the foraging requirements of the seabird community at Ashmore Reef.

Conclusions

This paper concatenates and summarizes existing data concerning seabird populations at Ashmore Reef. Many of these populations are internationally significant and all meet one or more criteria as matters of national environmental significance. Breeding seabirds have clearly benefitted from the protection and increased enforcement that has arisen following the designation of the area as a national nature reserve. Previous monitoring of bird populations at Ashmore Reef, whilst *ad hoc*, has provided valuable insights into the recovery of populations. More recently a seabird monitoring program that seeks to rigorously assess seabird population trends and changes within the reserves has commenced (April 2010). It is recommended that monitoring using the established techniques continue on a biannual basis. It is further recommended that consideration be given to establishing a program to rigorously assess the use of marine resources by Ashmore's seabirds outside of the reserve boundaries.

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Shorebirds of the Kimberley Coast – Populations, key sites, trends and threats

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Abstract

The tidal flats of the Kimberley coast support the largest populations of migratory shorebirds in Australia. In this paper we review and discuss population sizes of all 41 shorebird species occurring on the Kimberley coastlines, and summarise the importance of the region in an international context. The Kimberley coastline is used by c. 3.7 million shorebirds, including c. 635,000 migrants from the northern hemisphere and c. 16,000 Australian-bred resident shorebirds which forage on the tidal flats of the Kimberley coast. A further c. 3.06 million migratory shorebirds from near-coastal grasslands (Oriental Plover, Little Curlew and Oriental Pratincoles) use roosts on the Kimberley coast at times. Most coast-dependent shorebirds of the Kimberley are concentrated in a small number of sites. Eighty-mile Beach and Roebuck Bay are the most important two sites; they have the highest numbers of birds, and the greatest diversity of species occurring in internationally significant numbers. Internationally important numbers of several species occur on some offshore islands (Adele Island, Ashmore Reef and the Lacepedes), including several species (e.g. Lesser Sand Plover, Grey Plover, Grey-tailed Tattler and Ruddy Turnstone) which are disproportionately abundant on offshore islands when compared to the mainland. Although most of the key shorebird sites on the Kimberley coast are remote and have not been greatly affected by humans, there are indications that populations of many migratory species on the Kimberley coast are declining, probably because of habitat loss in the east Asian areas where they stage on migration. Continued and enhanced monitoring of shorebirds in the Kimberley that contributes strategically to the conservation management of this group is strongly recommended.

Keywords: shorebirds, Kimberley Coast, tidal flats

Introduction

Scope of this paper

Shorebirds, also known as 'waders', are smallish, mostly long-legged birds in the avian order Charadriiformes. They include the plovers and lapwings (family Charadriidae); curlews, godwits, snipe and sandpipers (family Scolopacidae); the oystercatchers (family Haematopidae); stilts and avocets (family Recurvirostridae); stone-curlews (family Burhinidae); jacanas (family Jacanidae) and painted snipe (family Rostratulidae). Most shorebird species are dependent on coastal or freshwater wetlands, and many species (especially in the families Charadriidae and

Scolopacidae) are strongly migratory, breeding in the far-northern hemisphere and migrating thousands of kilometres to distant non-breeding grounds. Australia is the regular non-breeding destination for about 38 migrant species, and the breeding region for 18 resident shorebird species; c. 23 further species have occurred as vagrants (Marchant & Higgins 1993, Higgins & Davies 1996, Christides & Boles 2008).

Shorebirds are studied by a community of amateur and professional ornithologists in Australia, inspired by the attractive appearance of the birds themselves, their spectacular migrations, and concern about the conservation threats that they face. Many non-breeding shorebird populations in Australia are declining (Gosbell and Clemens 2006; Wilson *et al.* 2011), despite the facts that migratory shorebirds are protected under the

Environment Protection and Biodiversity Conservation Act 1993, and that Australia is signatory to a number of international conservation agreements which list migratory shorebirds. These include the Ramsar Convention on Wetlands of International Importance (Department of Foreign Affairs 1975), the Japan – Australia Migratory Bird Agreement (Department of Foreign Affairs 1981), the China – Australia Migratory Bird Agreement (Department of Foreign Affairs 1988) and the Republic of Korea – Australia Migratory Bird Agreement (Department of Foreign Affairs 2007).

North Western Australia leapt to prominence in the shorebird biology world in the early 1980s. The Royal Australasian Ornithologists Union (now Birds Australia) was in the early stages of the first national project to assess shorebird populations in Australia when reports emerged of extraordinarily high shorebird numbers in Roebuck Bay and on the shores of Eighty-mile Beach (Minton & Martindale 1982, Minton 2006). Follow-up surveying revealed these sites to be the most important shorebird sites in Australia, and the most important non-breeding grounds known for shorebirds in the East Asian – Australasian Flyway (Lane 1987; Watkins 1993; Bamford *et al.* 2008).

In this paper, we draw together results from shorebird surveys carried out along the Kimberley coast to present a revised estimate of the number of shorebirds that occur in the region. We aim to present estimates based on recent surveys; it cannot be assumed that all historical counts are acceptable estimates of current numbers, given that there is emerging evidence that many shorebird species are declining in Australia (*e.g.* Gosbell and Clemens 2006). We restrict our attention to high tide roosts on the coast from Eighty-mile Beach to the border of Western Australia and the Northern Territory, including offshore islands (Fig. 1). Gulls and terns were usually counted in the surveys we summarise, but the surveys were designed to optimise counts of shorebirds rather than seabirds; we have excluded gulls and terns from this paper. Important shorebird populations occur in the Port Hedland region, and further south on the Pilbara coast. Although these regions are sometimes aggregated as 'North Western Australia' in the shorebird literature, we have not included them in this paper as they are far outside the Kimberley region. Nor have we attempted to summarise shorebird numbers on the freshwater wetlands of the Kimberley. Although shorebird surveys have not been conducted systematically in the area for long enough to carry out a comprehensive analysis of population trends, we present some preliminary results indicative of ongoing declines, and discuss potential threats to shorebirds of the Kimberley coastline.

Previous shorebird studies on the Kimberley coast

Since 1981, Roebuck Bay has become an international centre for shorebird research, with the shorebird populations there stimulating a long series of expeditions by the Australasian Wader Studies Group (AWSG) and the establishment of Broome Bird Observatory, and these in turn stimulating the establishment of a number of studies by visiting and resident researchers (Minton 2006). Banding studies by the AWSG, now supplemented

by more intensive studies by post-graduate students and the Global Flyway Network (an international partnership of researchers carrying out long-term demographic studies of long-distance-migrant shorebirds, <http://www.globalflywaynetwork.com.au/>), have revealed the essentials of the migration routes and strategies of many of the shorebird species of Roebuck Bay and Eighty-mile Beach; these essentials are presumably shared by shorebirds at other sites of the Kimberley coast. Most migratory species in the region are believed to use North Western Australia as a non-breeding area, where adults stay for several months (from about late August/September to March/April, exact timing differing between species) while carrying out their annual flight-feather moult (Minton *et al.* 2006). In a few species, such as Sharp-tailed Sandpiper *Calidris acuminata*, some adults stage on the coast of the Kimberley before migrating further south. Many migratory shorebird species on the Kimberley coast have delayed maturity, and after arriving in North Western Australia within 3–5 months of fledging in the northern hemisphere, they remain there for 1–3 years before they first attempt to migrate north (Rogers *et al.* 2006a). As a result, migratory shorebirds can be found on the Kimberley coast at all times of year, but numbers are lowest during the dry season (about May to early August) when adults are breeding in the northern hemisphere and only immature shorebirds remain in Australia.

Recaptures, resightings and remote observations of shorebirds that were banded, leg-flagged or satellite-tagged in North Western Australia have also revealed a great deal about the migration routes of our migratory shorebirds. Most species migrate in extremely long direct flights of several thousand kilometres. For example, leg-flag resightings and the correspondence between departure dates from Roebuck Bay and arrival dates in the Yellow Sea, indicate that Red Knots *Calidris canutus* and Great Knots *Calidris tenuirostris* migrate to the shores of the Yellow Sea in a single uninterrupted flight of 6,000 to 8,000 km (Battley *et al.* 2000, 2005; Rogers *et al.* 2010). Satellite telemetry has confirmed that a similar flight is made by Bar-tailed Godwits (Global Flyway Network; R. J. Gill, T. Piersma and colleagues in prep.). These enormous flights, lasting some 5–10 days, are fuelled by stores, especially fat, that the birds build up in the 1–2 months preceding migration (*e.g.* Piersma *et al.* 2005). Shorebirds almost double in mass before undertaking trans-equatorial migrations, so are strongly dependent on high-quality feeding grounds (Battley *et al.* 2000; Piersma *et al.* 2005b).

There can be little doubt that the Kimberley coastline does provide high-quality feeding grounds for shorebirds. It is dominated by very large tidal ranges (exceeding 9 m on many spring tides, and even higher in King Sound), and along much of the coast low tides expose extensive tidal flats, many kilometres wide. Tidal flats are the preferred foraging habitat for many shorebird species on the Kimberley coast, and over 15 of these species (including knots and godwits mentioned above) do not regularly feed in any other habitat during the non-breeding season. Moreover, surveys to assess the biomass and diversity of macrozoobenthos have demonstrated that potential shorebird prey is extraordinarily diverse and abundant in the tidal flats of Roebuck Bay (Pepping *et al.* 1999a, de Goeij *et al.* 2003).

and Eighty-mile Beach (Piersma *et al.* 2005a; Honkoop *et al.* 2006).

Shorebirds forage when walking or wading, and tidal flats are only accessible to them when the tide is low. High tides force them to sites known as roosts (whether they actually sleep there or not). Roost-choice studies in Roebuck Bay (Rogers *et al.* 2006b, 2006c) have demonstrated that potential roost sites are only suitable if they have a combination of physical attributes, including wet substrates (so shorebirds can avoid heat stress in exposed tropical conditions; Battley *et al.* 2003), open terrain (so approaching predators can be detected and avoided), and proximity to feeding areas (to keep commuting costs low). If suitable roost sites are unavailable, or are made inhospitable by frequent disturbance, shorebirds may be obliged to desert feeding areas (Rogers *et al.* 2006c). It is not known if roost site availability limits shorebird numbers in the Kimberley, but it is possible at some sites, as much of the Kimberley coastline is fringed by mangrove forests (Johnstone 1990) which are too dense for roosting shorebirds.

The roost choice studies in Roebuck Bay also enhanced shorebird surveying and monitoring projects in the region, as they led to an understanding of which seasons and tide conditions would lead to all shorebirds at specific sites using roosts which are accessible to counting teams (Rogers *et al.* 2006d). As a result, the main shorebird counts in the region are now carried out on carefully selected high tides between October and December (before the onset of wet season rains).

Methods

We examined shorebird count data from: (1) the Monitoring Yellow Sea Migrants in Australia (MYSMA) project outlined in Rogers *et al.* (2006d); (2) published literature and reports; (3) the shorebird count database at Birds Australia, which includes data from the AWSG's Population Monitoring Project, from the Atlas of Australian Birds and from the Shorebirds 2020 project. Except where stated, all results summarised here are from ground-counts at high tide roosts, carried out by experienced observers with binoculars and tripod-mounted telescopes. Experienced observers are essential for shorebird surveys in some sites of the Kimberley coast, where thousands, even tens of thousands, of shorebirds congregate in tightly-bunched and highly diverse flocks. Most results presented are from surveys carried out between late October and early December. This is considered the best time of year to survey shorebirds on the Kimberley coast because: (1) Most migratory shorebirds arrive on the coast of North Western Australia between August and mid-October (Minton *et al.* 2006; D.I. and K.G. Rogers, unpubl. data), so counts carried out earlier in the season are unlikely to represent peak numbers; (2) After wet-season rains begin, a varying and usually unknown proportion of coastal shorebirds begin to roost on clay-pans and other supra-tidal habitats that are usually inaccessible to human observers (Rogers *et al.* 2006b); moreover, access to even the more accessible roosts may become problematic in wet years when tracks are closed.

Site-specific notes on the survey data available, and the count methodology used, are given below. We only

present the results of complete site counts. Shorebird sites usually have a number of different roost sites within them, and we only consider a site count to have been complete if every component roost was visited, in circumstances in which double-counting is unlikely to have occurred. Sources of error in shorebird counts have been reviewed by Rappoldt *et al.* (1979) and, in North Western Australia, by Rogers *et al.* (2006d). Both studies concluded independently that some of the variation observed in shorebird counts is caused by stochastic error, which can be quantified in a rigorous manner.

Genuine inaccuracies in counts can also occur. Most often, these are caused by flocks of birds being overlooked, and therefore maximum counts are a useful way to present shorebird count data, as they may be more representative of the number of birds that a site is capable of holding than mean counts skewed by individual counts in which birds were overlooked. On the other hand, maximum counts might themselves represent outliers. In this paper, we present maxima, but in the annotated species list (results) we also make specific notes in situations where there is a striking discrepancy between maximum and average counts.

We focus on Kimberley sites where at least one shorebird species has been found to occur in internationally significant numbers (Fig. 1) – i.e. >1% of the flyway population estimated by Bamford *et al.* (2008). They include Roebuck Bay, Eighty-mile Beach and three offshore island groups (Adele Island, Ashmore Reef and the Lacepedes). Most of these sites are difficult to access, and have not been surveyed many times. As data are thin, it was not possible to follow a uniform approach in summarising approximate numbers at each site. Data selection for each site is described below, and notes are provided on count methodology.

Roebuck Bay

Shorebird counts were initiated in Roebuck Bay (Fig. 2) in the early 1980's, but it was only in 1999 that it became conventional practice to carry out surveys in October to November, and only in 2004 when resources were first obtained to carry out counts at Bush Point (an important roost in the south of the bay) on a regular basis. Accordingly, in our summary of mean and maximum counts from Roebuck Bay we only present data collected since 2004, presenting the sum of complete counts carried out on the northern beaches and Bush Point on the same tide series. Two summer counts (late October to early December) and one winter count (June to July) were carried out annually in this period.

A series of beaches used by roosting shorebirds occur along the northern shores of Roebuck Bay, including Town Beach and Simpson's Beach adjacent to the Broome township. When conditions are dry (e.g. in the period before wet season rains begin in mid to late December), and tide height is between 6.8 and 9.0 m, these are the only roosts used by shorebirds from the northern tidal flats of Roebuck Bay (Rogers *et al.* 2006 b, c, d)¹. Higher

¹ Optimal tide height in for shorebird counts in Rogers *et al.* (2006 b, c) was reported to be 6.0 to 8.2 m; since then the datum in Broome tide charts from the National Tidal Centre has been increased by 0.86 m, a convention we follow in this paper

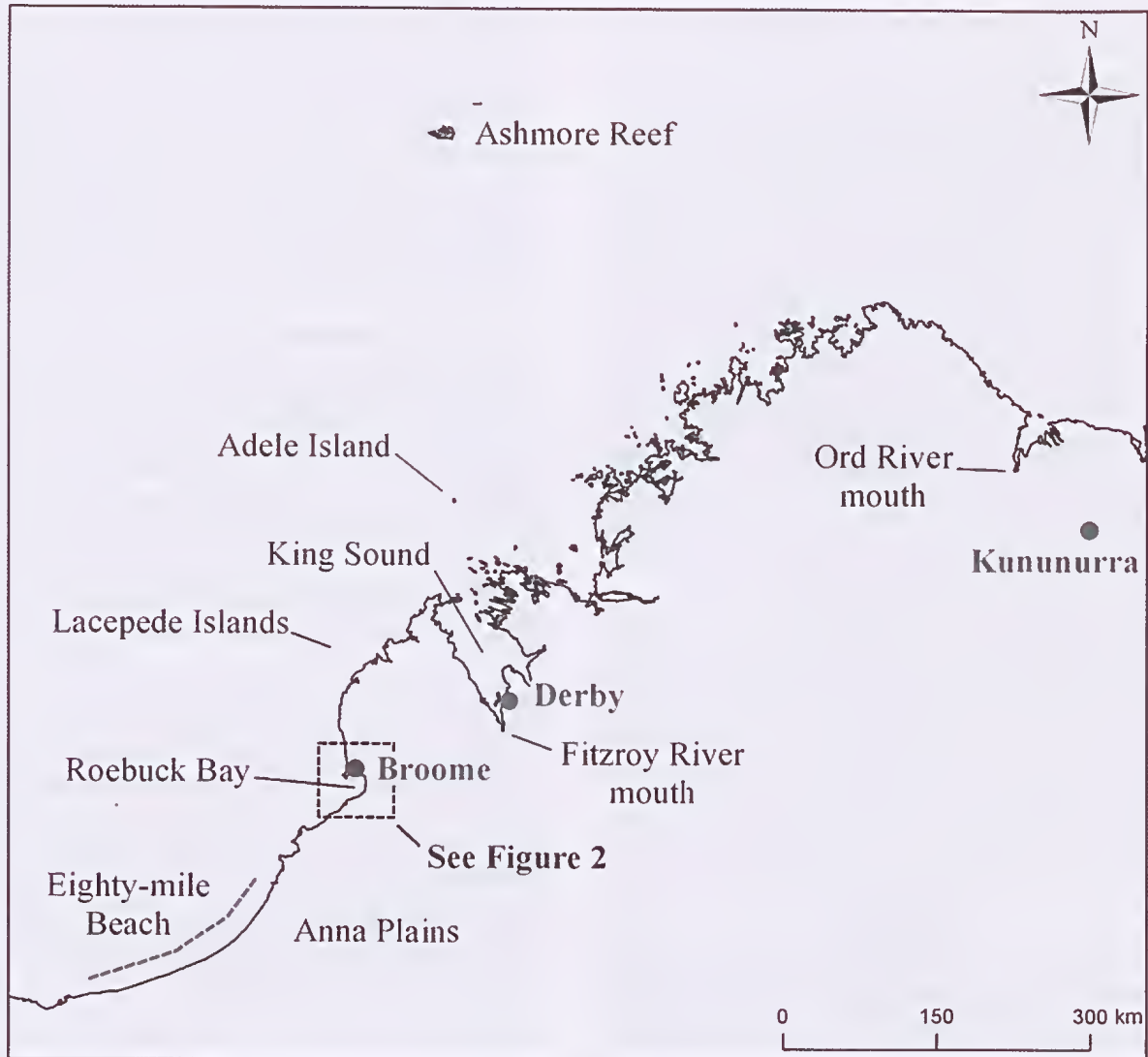


Figure 1. Shorebird sites of the Kimberley coast.

tides flow into mangrove clearings and claypans behind the mangroves; these become preferred roosting sites when wet, but are mostly inaccessible to human observers. During periods of neap tides, high tides are lower than 6.8 m, and are not high enough to push all shorebirds from the tidal flats. Tides between 6.8 m and 7.2m do not keep shorebirds on the northern beaches for long enough for adequate counts, so counts of the northern beaches of Roebuck Bay are carried out on tides between 7.2 and 9.0 m high.

Shorebirds foraging on the tidal flats in the southern half of Roebuck Bay do not roost on the northern beaches; instead they fly south to roost at or near Bush Point. Bush Point can be counted most repeatably on tides between 8.8 and 9.7 m high; on lower tides aerial and hovercraft surveys have shown that some shorebirds find roosts on sandbanks or mudbanks in front of the mangrove fringe which are very difficult for humans to access. Vehicle access to Bush Point is not possible on tides greater than 9.7 m high and such tides also create potential alternate roosting sites in the saltmarsh.

Radio-telemetry studies (Rogers *et al.* 2006 b, c) have shown that within a spring tide series, there is virtually

no movement of Great and Red Knots to Bush Point from the northern beaches of Roebuck Bay. However, colour-band resightings indicate that some birds can move from the north to the south of Roebuck Bay over longer time frames (C J Hassell unpubl. data), with radio-telemetry suggesting these relocations typically occur during neap tides, when tidal flat areas are restricted and high tides are too small to be suitable for shorebird surveys (Rogers *et al.* 2006b. and unpubl. data). We therefore consider coupled counts of Bush Point and the northern beaches of Roebuck Bay on the same tide series (not separated by a neap tide series) to be complete counts of Roebuck Bay. A few shorebirds that sometimes roost in mangroves may be overlooked, (e.g. Common Sandpiper, and possibly some Whimbrel, Terek Sandpiper and Grey-tailed Tattlers) but both radio-telemetry and aerial surveys indicate that there are no other major roosts for shorebirds in the area in the tide conditions when we carry out surveys.

Eighty-mile Beach

Despite its name, Eighty-mile Beach is c. 220 km (c. 138 miles) long, and undertaking a complete count of the

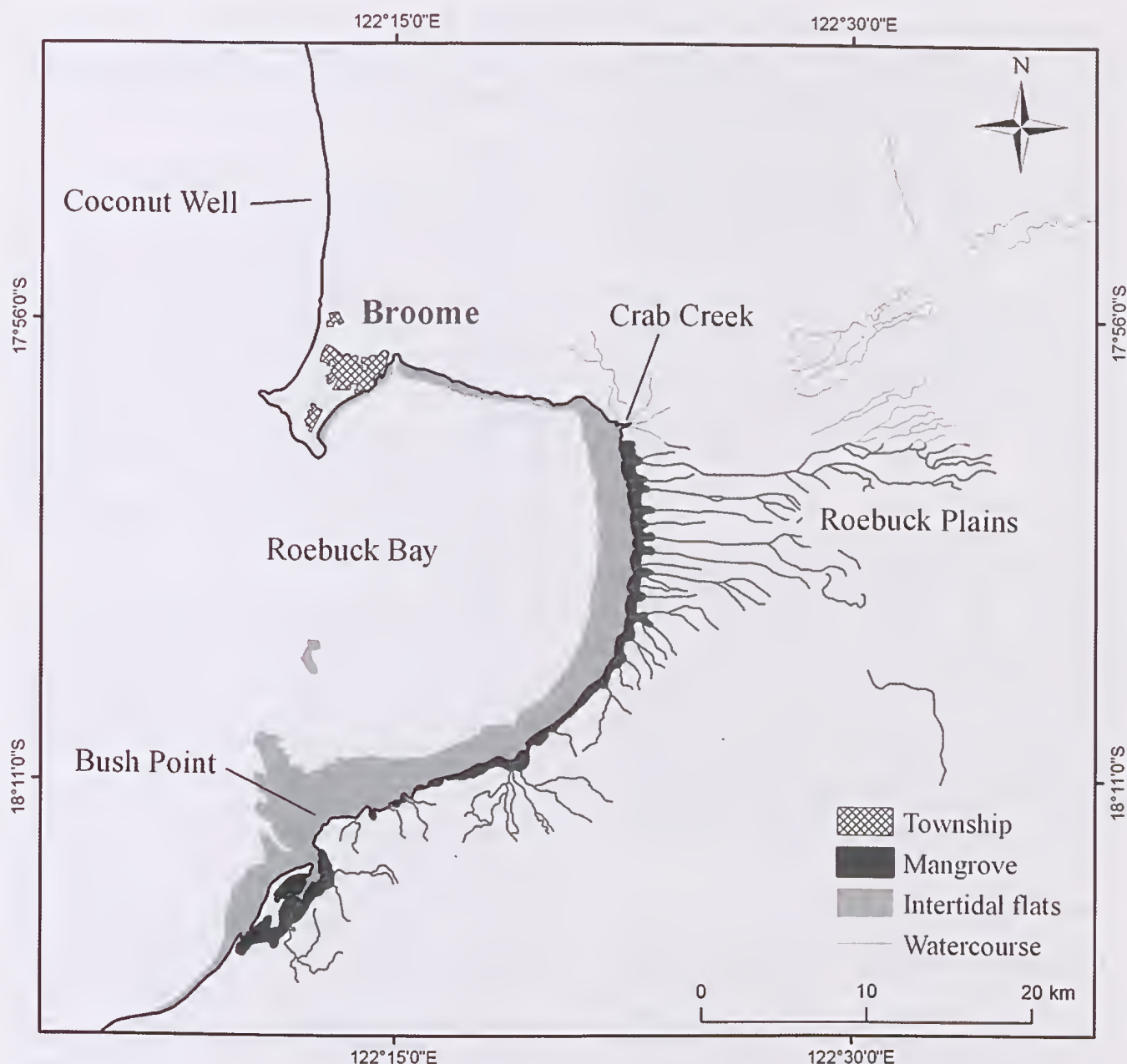


Figure 2. Shorebird sites in the Roebuck Bay area.

beach is difficult. In addition to the size and remoteness of the beach, counting shorebirds there requires exceptionally experienced teams, as the site has non-breeding populations of hundreds of thousands of shorebirds, occurring in very large mixed flocks.

Estimates of the numbers of shorebirds occurring on Eighty-mile Beach were first published in the late 1980's (Lane 1987, Watkins 1993), on the basis of ground counts of sections of the beach, supplemented by aerial surveys. The aerial surveys were used to assess total shorebird numbers on the beach, but it was not possible to identify shorebirds to species level from the air. To make the first estimates of numbers of each species on Eighty-mile Beach, Lane (1987) therefore made extrapolations from the species composition observed during the limited ground counts.

Complete ground counts of Eighty-mile Beach were first managed in the late 1990s, and there have still only

been four complete ground surveys, in October 1998, November 2001, July 2003 and December 2008. These surveys showed that shorebird distribution is not consistent along all of Eighty-mile Beach. Some species are quite uniformly spread, but others occur in high densities along particular stretches of beach (differing between species). One such species with a particularly patchy distribution is the Red Knot; for example in 2008 the Red Knot population of 23,000 birds only used a 15 km stretch of Eighty-mile Beach (Rogers *et al.* 2009). As a result of the patchy distributions, previous estimates of shorebird numbers on Eighty-mile Beach based partly on extrapolation from limited ground counts must be treated with caution.

The complete surveys of Eighty-mile Beach also clarified the seasonal and tide conditions most suitable for surveying the site. Like Roebuck Bay, summer migrants are most repeatably counted about November,

after most or all birds have arrived from the northern hemisphere but before wet season and/or cyclone-associated rains have begun; in wet conditions vehicle access to the beach can become difficult and alternate roosting habitats can be created behind the coastal dunes. There are no tide charts available for Eighty-mile Beach but our experience is that time and height of high tides at this site are predicted reasonably well by tide charts for Roebuck Bay. Optimal tide heights for shorebird surveys are lower than those at Roebuck Bay, ideally between 6.8 and 7.9 m. On higher tides the beach becomes quite narrow in places, making it difficult to carry out counts without disturbing shorebirds and running the risk of double-counting them. Moreover, we suspect that on very high tides many shorebirds on Eighty-mile Beach make longshore movements so they can roost on broader stretches of beach, where they are not forced close to elevated dune fronts, which might be used for cover by predators.

Adele Island

This small (3.6 × 1.6 km), low-lying island is surrounded by extensive tidal sandflats, several km wide at low tide. Several ornithologists have visited the island and made notes or incomplete counts of migratory shorebirds (e.g. Coate 1994, 1995, 1997; Swann 2002; Hassell 2003). Building on these experiences a four-person team carried out a complete count of shorebirds on the island in December 2004 (Boyle *et al.* 2005). Over a five day period they found that counts were best carried out on higher tides, which submerged sandbars on which shorebirds preferred to roost but were difficult to access. As the shorebirds were scattered it was necessary to split the team into two groups counting different areas simultaneously.

Ashmore Reef

A number of shorebird surveys have been undertaken on the islands and sandbanks of Ashmore Reef since 1979, but only four of these surveys are believed to have been complete, including counts of all high tide roosts on all islands. These surveys were undertaken in January 2002, February 2003, January 2005 and April 2010 (Swann 2005a, 2005b, 2005c and Clarke 2010). Complete counts can be conducted over a 4–5 day period and require predicted high tides at West Island, Ashmore Reef of between 3.5 and 4.0 m. This tidal range ensures birds are unable to occupy additional sandbanks that would be available on lower tides whilst also providing sufficient depths to access all islands and remaining sandbanks by water craft. We present the data summarised by Clarke (2010), who collated previous surveys and calculated maximum counts for the reef, in some cases including totals from partial surveys where they exceeded totals counted during the complete surveys.

Lacepede Islands

Data were available from six complete shorebird surveys on the Lacepede Islands: 15–19 December 1997 (Swann and Willing 1997), 1 September and 14 October 1998 and 9 October 1999 (AWSG unpubl. data), 26 September 2003 (AWSG unpubl. data) and 25 November 2004 (A Boyle, G Swann, T Willing, T Gale & L Collins

unpubl. data). Although the islands are not large, a team of several persons is helpful for surveying these sites, as shorebirds need to be counted concurrently on four separate islands.

Other sites

There were aerial surveys for shorebirds of the entire mainland Kimberley coastline in the 1980's (Lane 1987, C D Minton unpubl.) and these were repeated in November 2008 (Kingsford *et al.* 2010). Both surveys were consistent in finding no major shorebird concentrations on the coast anywhere except Roebuck Bay and Eighty-mile Beach. The aerial surveys in the 1980's have influenced subsequent ground counts of shorebirds in the region, with observers only tackling the logistical difficulties of ground counts in areas which aerial surveys have suggested to be promising. For this reason, and also because of the remoteness of much of the coastline, there have been no systematic ground counts of shorebirds (that we are aware of) on any of the mainland coast between King Sound and the Northern Territory border. There has been patchy surveying of King Sound itself (Hassell 1997).

The south-west coast of the Dampier Peninsula, from Cable Beach to about Quondong, is regularly visited by Broome-based birdwatchers, but surprisingly few systematic shorebird counts have been carried out there and submitted to count databases. In this report we could only draw on the counts reported by Rogers *et al.* (2009); they were mostly consistent with the general qualitative experience of local birdwatchers in this area.

There is a stretch of coastline some 130 km long between Eighty-mile Beach and Roebuck Bay, with a number of shallow marine embayments that look potentially suitable for shorebirds. The only systematic ground counts of these sites that we are aware of were carried out in December 2008 (Rogers *et al.* 2009). The counts were made between 11th–13th December, on tides between 7.65 and 8.55 m high. Although the counts were 'cold', not informed by extensive former experience of the sites, they corresponded well with concurrent aerial survey and are considered reasonably accurate. We have pooled the data from several sites in our summary; details of the individual sites are given in Rogers *et al.* (2009).

Results

Shorebird numbers on the Kimberley coast

Maximum shorebird counts available for Kimberley coastal sites are presented in Table 1, along with East Asian – Australasian Flyway population estimates for each species from the literature. Forty-two shorebird species have been recorded on high tide roosts along the Kimberley coast, and 24 of these species occur on the coastline in internationally significant numbers (>1% of the flyway population). The combined population of all shorebird species on the Kimberley coast is 3.7 million shorebirds. These include c. 649,000 genuinely coastal shorebirds which forage on intertidal flats, 633,000 of which are migrants using the region as a non-breeding area; a further 16,000 are resident species. In addition, there have been counts of very large numbers of three

Table 1

Maximum shorebird counts at Kimberley coastline sites since 1999. Taxonomy and species order follows Christides & Boles (2008), except that migrant and resident species are separated; scientific names are given in the annotated species list in the results section. Flyway population estimates for migrants are from Bamford *et al.* (2008) except where otherwise stated in the text; population estimates for resident species are from Delany and Scott (2006). Species counts at internationally significant levels (>1% of the flyway population) are given in boldface.

	Eighty-mile Beach	Roebuck Bay	Adele Island	Ashmore Reef	Lacepede Islands	N of EMB	Dampier Peninsula	Total	1% threshold	Flyway population estimate
COASTAL MIGRANTS										
Pacific Golden Plover	73	103	120	746	119	29	35	1225	1000	100–1000K
Grey Plover	1585	697	564	1511	106	209	55	4727	1250	125000
Lesser Sand Plover	162	71	671	32	94	9	75	1114	1400	140000
Greater Sand Plover	64584	22318	2046	2559	636	3134	1423	96700	1100	110000
Swinhoe's Snipe				1				1	250	25–100K
Black-tailed Godwit	52	6780	2	8				6842	1600	160000
Bar-tailed Godwit	110290	25821	4819	4560	624	3414	52	149580	3250	325000
Whimbrel	363	1100	69	536	16	220	59	2363	1000	100000
Eastern Curlew	709	776	57	4	32	74	5	1657	380	38000
Eurasian Curlew	1	1						2	400	4000
Terek Sandpiper	9820	1522	604	216	45	165	2	12374	600	60000
Common Sandpiper	6	19	4	9	8	12	26	84	250	25–100K
Grey-tailed Tattler	14647	2173	5489	1791	2122	448	110	26670	500	50000
Common Greenshank	2534	533	239	590	53	1	6	3957	600	60000
Nordmann's Greenshank	1							1	10	1000
Marsh Sandpiper	171	5	4	1				181	1000	100–1000K
Common Redshank	5	1	1	1	1			9	750	75000
Ruddy Turnstone	3480	1044	1250	1708	2154	402	196	10234	350	35000
Asian Dowitcher	2	414		8				424	240	24000
Great Knot	169044	30361	2945	1592	1055	1561	212	206670	3750	375000
Red Knot	29679	2755	51	55	150		27	32717	2200	105000
Sanderling	3605	3235	449	1132	158	423	274	9276	220	22000
Little Stint				1				1		
Red-necked Stint	28443	16397	4107	1530	625	998	385	52485	3250	325000
Pectoral Sandpiper			1					1	250	25000
Sharp-tailed Sandpiper	205	263		3	102	1	8	582	1600	160000
Curlew Sandpiper	7984	1601	493	850	365	1	1	11295	1800	180000
Broad-billed Sandpiper	35	196	21	1				253	250	25000
GRASSLAND MIGRANTS										
Oriental Plover	144300	6431		2		66	2	150801	700	70000
Little Curlew	14200	1297		50				15547	1800	180000
Oriental Pratincole	2880000	21041	1	1	1			2901044	20000	2880000
RESIDENT SHOREBIRDS										
Bush Stone-curlew		2						2		
Beach Stone-curlew	1	2		1				4	250	
Australian Pied Oystercatcher	809	547	48		58	132	36	1630	110	11000
Sooty Oystercatcher	25	34			43	5	39	146	75	7500
Black-winged Stilt	10	381	2	14		2		409	250	25–100K
Red-necked Avocet		30						30	1100	1700
Red-capped Plover	6752	6531	14		38	613	159	14107	950	95000
Black-fronted Dotterel	1						2	3	160	15500
Masked Lapwing				1			2	3	10000	
Australian Pratincole	9			2	1			12	600	60000
Total shorebirds	3493587	154482	24071	19516	8606	13919	3191	3717364		
Total coastal migrants	447480	118186	24006	19447	8465	13101	2951	633628		
Total grassland migrants	3038500	28769	1	53	1	66	2	3067392		
Total residents	7607	7527	64	18	140	752	238	16346		

grassland species (Oriental Pratincole, Oriental Plover and Little Curlew) which do not feed on the tidal flats of the Kimberley coast, but use surf-dampened beaches as a relatively cool loafing site in hot conditions.

The great majority of coastal shorebirds in the Kimberley region occur on two sites: Eighty-mile Beach (> 450,000 intertidal shorebirds; 19 species found in internationally significant numbers), and Roebuck Bay (> 113,000 shorebirds; 17 species found in internationally significant numbers). Offshore islands (Adele Island, Ashmore Reef) and the Lacepede Islands also have internationally significant numbers of several shorebird species, with counts of some of these species (notably Ruddy Turnstone, Grey-tailed Tattler, Sanderling and Grey Plover) being proportionately high compared to mainland sites. Surprisingly few shorebirds occur elsewhere along the Kimberley coast (see Discussion). An annotated species list below discusses the status of each species.

Coastal migrants

Pacific Golden Plover, *Pluvialis fulva*. No single Kimberley site holds internationally significant numbers of this species, but counts of >700 on Ashmore Reef are noteworthy, and the Kimberley coast as a whole supports more than 1% of the flyway population. Pacific Golden Plovers tend not to join large shorebird flocks in the Kimberley, instead occurring in small groups in localised sites; there are also records of the species foraging on inland plains in the company of Oriental Plovers, so it is likely that the number occurring in the Kimberley is underestimated.

Grey Plover, *Pluvialis squatarola*. Internationally significant numbers occur regularly on Eighty-mile Beach and Ashmore Reef. The large numbers (hundreds) occurring in Roebuck Bay and on Adele Island would once have qualified as internationally significant, before the flyway population size of Grey Plover was reappraised by Bamford *et al* (2008) and found to be larger than previously thought. Nevertheless, it could be argued that Roebuck Bay and Adele Island are of international importance to Grey Plovers, as more than 1% of the adult female Grey Plover of the East Asian – Australasian Flyway occur in these sites; this species shows strong differential migration in the East Asian – Australian flyway, and nearly all Grey Plover in Australia are female (Marchant & Higgins 1993; D I Rogers, C D T Minton, K-M Exo *et al.* in prep.). There is an historical count of 1300 Grey Plovers in Roebuck Bay, but no more than 700 Grey Plover have been seen in Roebuck Bay surveys since 2004.

Semi-palmated Plover, *Charadrius semipalmatus*. This vagrant has been recorded once during a shorebird count, on the shores of Roebuck Bay in the summer of 2010.

This individual had been present for a year and was the first Australian record on discovery. A second individual (the fourth Australian record) occurred briefly in Roebuck Bay while the first bird was still present (A.N. Boyle and G. Swann unpubl.).

Lesser Sand Plover, *Charadrius mongolus*. Although distinctive when examined closely, this species is easily

confused with the similar Greater Sand Plover during shorebird counts. Previous reports of over 1000 in Roebuck Bay in 1990 and of 550 at Ashmore Reef prior to 1998 may have been influenced by misidentifications by observers who may, on the basis of eastern Australian experience, have incorrectly anticipated Lesser Sand Plover to be the more numerous of the two species. In fact Greater Sand Plovers far outnumber Lesser Sand Plovers in North Western Australia, and more recent surveys by teams with more local experience have been consistent in finding Lesser Sand Plovers to be uncommon and patchily distributed on the Kimberley coast and most offshore islands. No Kimberley sites are known to have internationally significant numbers of Lesser Sand Plovers, but confirmed counts of almost 700 on Adele Island (Boyle *et al.* 2005) are noteworthy.

Greater Sand Plover, *Charadrius leschenaultii*. Internationally significant numbers occur on Eighty-mile Beach, Roebuck Bay, Adele Island, Ashmore Reef and the Dampier Peninsula. Collectively, over 85% of the Flyway population of Greater Sand Plover occurs on the Kimberley coast.

Black-tailed Godwit, *Limosa limosa*. Internationally significant numbers occur in Roebuck Bay, mainly feeding on the soft tidal flats at the mouth of Crab Creek at low tide, and at high tide roosting on the adjacent northern beaches. Numbers there fluctuate, and summer counts since 2004 have ranged from 116 to 1975 birds (average 693). Higher counts have been made in the past (e.g. 6780 in November 2001; three counts of 2000–4000 in Feb–Dec. 1999). It is not known if the lower counts in recent years reflect declines, or variation typical for the species. Black-tailed Godwits also make use of fresh inland wetlands, and it is possible that the highest counts in Roebuck Bay occur in dry conditions when there is least wetland habitat inland.

Bar-tailed Godwit, *Limosa lapponica*. Internationally significant numbers occur in Roebuck Bay, Eighty-mile Beach, Adele Island and Ashmore Reef. Collectively Kimberley coastline and offshore island sites hold over 45% of the flyway population of Bar-tailed Godwits. The subspecies occurring in North Western Australia is the Siberian-breeding *menzbieri*, and it is likely that the Kimberley coast holds most of the non-breeding population of this subspecies. The eastern limits of the range of *menzbieri* are poorly known, but it is rare to absent in eastern Australia and New Zealand, where subspecies *baueri* predominates.

Whimbrel, *Numenius phaeopus*. Internationally significant numbers occur in Roebuck Bay, but it is relatively uncommon on Eighty-mile Beach and on most of the offshore islands of importance for other shorebird species. Unlike Roebuck Bay, these sites lack extensive mangrove stands. Whimbrel on the Kimberley coast seem to be most abundant near mangroves, where they forage for crabs both at low tide (on tidal flats) and often at high tide (at the interface of mangroves and saltmarsh). The species can also roost in mangroves at times, making it difficult to count; in Roebuck Bay the numbers seen setting off on northwards migration exceed those observed on high tide roosts. We think it is likely that available data considerably underestimate numbers on the Kimberley coast.

Eastern Curlew, *Numenius madagascarensis*. Internationally significant numbers occur in Roebuck Bay and Eighty-mile Beach; collectively the Kimberley coastline holds about 4% of the flyway population.

Eurasian Curlew, *Numenius arquata*. A vagrant; the only confirmed Australian records are from Eighty-mile Beach and Roebuck Bay.

Terek Sandpiper, *Xenus cinereus*. Over 20% of the flyway population occurs on the Kimberley coastline, mainly in Roebuck Bay and on Eighty-mile Beach.

Common Sandpiper, *Actitis hypoleucos*. This species occurs in low densities, does not typically roost in flocks, and prefers sites with narrow or steep shorelines, such as mangrove systems and sheltered rocky coastlines. Its numbers on the Kimberley coastline are therefore likely to be greatly underestimated during standard shorebird surveys.

Grey-tailed Tattler, *Tringa brevipes*. Over 50% of the flyway population occurs on the Kimberley coast. Over 35% of these birds occur on the tidal flats of small offshore islands (Adele Island, Ashmore Reef and the Lacepedes), and internationally significant numbers also occur on Eighty-mile Beach and Roebuck Bay.

Common Greenshank, *Tringa nebularia*. Internationally significant numbers regularly occur on Eighty-mile Beach, especially in the October–December period before wet season rains create alternate habitats in inland wetlands. Numbers in Roebuck Bay and Ashmore Reef also approach internationally significant levels.

Nordmann's Greenshank, *Tringa guttifer*. This endangered migratory shorebird has only been recorded twice in Australia. Both records are of single individuals on Eighty-mile Beach found during shorebird counts (Birds Australia Rarities Committee, cases 519 and 673).

Marsh Sandpiper, *Tringa stagnatilis*. A migrant which occurs mainly on inland wetlands during the non-breeding season. Small numbers (up to a few hundred on Eighty-mile Beach) occur on the Kimberley coastline, mainly in the October–December period when inland wetlands are most likely to be dry.

Common Redshank, *Tringa totanus*. Annual visitor in very small numbers; the non-breeding strongholds of this species are north of Australia. It occurs regularly at Crab Creek in Roebuck Bay.

Ruddy Turnstone, *Arenaria interpres*. The Kimberley coastline is used by almost 30% of the flyway population during the non-breeding season, and resightings of leg-flagged and colour-banded birds suggest that additional birds stage in the area during southwards migration. Over half the Kimberley population occurs offshore, on Adele Island, Ashmore Reef and the Lacepede Islands. Internationally important numbers also occur in Roebuck Bay and Eighty-mile Beach.

Asian Dowitcher, *Limnodromus semipalmatus*. The non-breeding stronghold of this species is on the coast of Sumatra, but internationally significant numbers have also been recorded in Roebuck Bay. The status of Asian Dowitchers in North Western Australia is puzzling. A feeding flock of 414 birds was recorded at the mouth of Crab Creek in Roebuck Bay in 2000 (Rogers *et al.* 2000); 212 were found in the same site a year later (C. J. Hassell

pers. obs.) but there have been no other counts exceeding 150 birds. Nevertheless, this count was consistent with the tendency for Asian Dowitchers to be most abundant in Roebuck Bay in March/April, when counts on the northern beaches regularly approach 100 birds. Typically some non-breeding dowitchers remain on the northern beaches of Roebuck Bay during the austral winter, but (unlike all other migrant species in North Western Australia) numbers decline inexplicably during September and October, with very few being present in the October to December period.

Great Knot, *Calidris tenuirostris*. Internationally significant numbers occur in several sites on the Kimberley coast, notably at Eighty-mile Beach (which holds 45% of the flyway population) and Roebuck Bay (8% of the flyway population). Collectively over 55% of the flyway population occurs on the Kimberley coast during the non-breeding season.

Red Knot, *Calidris canutus*. Until recently, the flyway population of this long-distance migrant was thought to be about 220,000 (Bamford *et al.* 2008), but a recent revision showed the actual population is only *c.* 105,000 (Rogers *et al.* 2010). The Kimberley population (over 30% of the flyway population) includes at least 50% of the global population of subspecies *piersmaei* from the New Siberian Islands. In the late 1980s the Eighty Mile Beach was estimated to support *c.* 80,000 Red Knot (Lane 1987, Watkins 1993), on the basis of partial ground counts supplemented by aerial survey. However, complete ground counts conducted since then have been consistent in finding only 20–30,000 Red Knot. We suspect that the high initial estimate was in error but cannot rule out the possibility that the discrepancy with subsequent counts has been caused by population decline.

Sanderling, *Calidris alba*. Over 30% of the flyway population occurs on the Kimberley coastline, with internationally significant numbers occurring in Roebuck Bay (mainly at Bush Point), Eighty-mile Beach, Ashmore Reef and the west coast of the Dampier Peninsula. We believe the only Dampier Peninsula count available to us to be an underestimate of the number of Sanderling that use this coastline, as regular sightings of over 500 Sanderling have been at one Dampier Peninsula site (Coconut Well; A. N. Boyle unpubl.), especially during southwards migration when some individuals stage in the region before migrating further south.

Little Stint, *Calidris minuta*. One record from Ashmore Reef during counts and occasional records elsewhere along the Kimberley coastline. This species is very difficult to distinguish from Red-necked Stint and is probably overlooked at times, but it is clear from banding studies that the species only occurs in the region as a vagrant.

Red-necked Stint, *Calidris ruficollis*. About 16% of the flyway population occurs on the Kimberley coastline, with internationally significant numbers on Eighty-mile Beach, Roebuck Bay and Adele Island during the non-breeding season. Resightings of leg flags suggest that additional Red-necked Stints may stage on the Kimberley coast during southwards migration.

Pectoral Sandpiper, *Calidris melanotos*. The single record on Adele Island was probably a disoriented staging

individual; the species typically prefers freshwater wetlands.

Sharp-tailed Sandpiper, *Calidris acuminata*. Numbers peak on the Kimberley coast about September to October. Some birds remain through the wet season, but many only stage in the area before migrating inland, or further south, for the non-breeding season.

Curlew Sandpiper, *Calidris ferruginea*. Internationally significant numbers occur on Eighty-mile Beach. The numbers occurring on Roebuck Bay and Ashmore Reef are probably also internationally significant, especially as there is evidence from banding studies suggesting that some individuals stage in North Western Australia during southwards migration; numbers observed in November counts may therefore not include all birds that depend on the area as a feeding ground while staging. There is an urgent need to review the flyway population of this species, as it has undergone serious declines since the 1980's in all Australian sites for which monitoring data are available (Gosbell and Clemens 2006).

Broad-billed Sandpiper, *Limicola falcinellus*. Numbers in Roebuck Bay approach internationally significant levels. Two hundred were counted by Broome Bird Observatory on the northern shores of Roebuck Bay on 25 October 2009; as the important roost at Bush Point was not visited at the time, it is likely that further birds were present in the bay.

Grassland migrants

Oriental Plover, *Charadrius veredus*. Although this plover forages on grasslands rather than tidal flats, large numbers are regularly seen at high tide coastal roosts on Eighty-mile Beach, and sometimes in Roebuck Bay. They use these sites as a thermal refuge in the middle of the day, as they can loaf on wet sand in a sea breeze, experiencing a much cooler microclimate than that of the plains where they feed in the morning, the evening and through the night. The highest ever count of 144,000 birds was made on a 75 km stretch of Eighty-mile Beach in February 2010 (Piersma and Hassell 2010). It exceeds the previous estimate of the flyway population of this species (70,000 birds, Bamford *et al.* 2008), which is clearly in need of review. There had been several previous counts of 30–50,000 Oriental Plover along the same stretch of Eighty-mile Beach. It is suspected that the higher count in February 2010 reflected count logistics, as this survey targeted Oriental Plovers (and Oriental Pratincoles) in the middle of the day. In contrast previous surveys targeted 'tidal flat' shorebirds on morning high tides, and were concluded by 9–10 am, before temperatures had risen sufficiently to force all Oriental Plovers from their grassland feeding areas.

Little Curlew, *Numenius minuta*. Like Oriental Plover, this species forages on grasslands, but sometimes uses beaches of Eighty-mile Beach and Roebuck Bay as a thermal refuge in the heat of the day. The highest counts on these beaches were made in February 2010 (Piersma and Hassell 2010), at a time when large grasshopper swarms were present in the area. There have been other periods in the past (e.g. 1985) when tens of thousands of Little Curlew were present on Anna Plains and Roebuck Plains (C.D. T. Minton, pers. obs.), but did not roost in

large numbers on the coast because there were alternative thermal refuges beside freshwater wetlands.

Oriental Pratincole, *Glareola maldivorum*. This species made headlines in February 2004, when a team from the AWSG, on encountering unusually high numbers of pratincoles on Eighty-mile Beach, took the opportunity to charter a plane and undertake a systematic count. They recorded 2.88 million Oriental Pratincoles (Sitters *et al.* 2004) – an astonishing result given that the flyway population at the time was thought to be only 75,000 birds. At the time the high count was considered to be a one-off, caused by an unprecedented combination of high locust populations in the region and extraordinarily wet conditions through most of the rest of northern Australia. Since then, however, Piersma and Hassell (2010) have again encountered huge numbers of Oriental Pratincoles on Eighty-mile Beach, counting c. 515,000 Oriental Pratincoles along a 75 km stretch of beach in February 2010. Although such large numbers are not an annual occurrence, it now seems that Eighty-mile Beach may be used more regularly by huge numbers of Oriental Pratincole than was previously appreciated. Like Oriental Plovers, they do not forage on the tidal flats off Eighty-mile Beach; instead they forage over adjacent grasslands, but roost on Eighty-mile Beach during the hottest time of day.

Resident species

Bush Stone-curlew, *Burhinus grallarius*. A terrestrial species; the very occasional records on the shores of Roebuck Bay presumably represent disturbed birds from nearby pindan woodlands.

Beach Stone-curlew, *Esacus magnirostris*. This coastal specialist is under-represented in standard high tide shorebird surveys; it typically occurs solitarily or in pairs, not joining large shorebird flocks. Aerial surveys suggest that it occurs in low densities but is widespread along the Kimberley coast, using habitats such as beaches and reefs (with some nearby mangroves or other near-shore vegetation which can be used for cover) which do not support high densities of other shorebird species, and have not been a focus for shorebird surveys. Nevertheless, much of the Kimberley coastline is dominated by rocky shores or extensive mangrove systems which are unsuitable for the species, and it is curiously absent from some sites (such as Eighty-mile Beach) where the habitat appears adequate. We do not think the Kimberley coast supports a large population of this species.

Australian Pied Oystercatcher, *Haematopus longirostris*. A coastal resident which nests on ocean beaches, mainly during the austral winter and spring, and can congregate in non-breeding flocks with other shorebird species during the wet season. The Flyway population estimate of 11,000 was made by Watkins (1993). Internationally significant numbers are regularly reported at Bush Point in Roebuck Bay (dominated by non-breeding subadult individuals). Eighty-mile Beach is also an internationally significant site for the species, but this was not recognised until 1999, as previous ground-counts of Eighty-mile Beach had not included the sections of the beach around Wallal Downs where Australian Pied

Oystercatchers are most abundant (perhaps because the low dunes behind this section of the beach are suitable for nesting).

Sooty Oystercatcher, *Haematopus fuliginosus*. A coastal resident which occurs mainly on rocky shores, though it can also be found on adjacent sandy beaches. Unlike the Australian Pied Oystercatcher, it prefers to nest on islands (such as the Lacepedes), with counts on the mainland being dominated by non-breeding flocks. The northern Australian subspecies *ophthalmicus* occurs in the Kimberley; it has been estimated to have a global population of 7,500 birds (Delany & Scott 2006). No single site in the Kimberley has been identified as having internationally significant numbers of Sooty Oystercatcher, but the region as a whole is likely to hold a large proportion of the flyway population, given that the species occurs at low densities along long areas of rocky coastline where no ground counts of shorebirds have been attempted.

Black-winged Stilt, *Himantopus himantopus*. Subspecies *leucocephalus* occurs as a resident from Australia to Indonesia, mainly in freshwater wetlands. Small numbers occur in some high tide roosts along the Kimberley coast, especially in Roebuck Bay where internationally significant numbers sometimes forage on sheltered tidal flats near Crab Creek. Much larger numbers, sometimes tens of thousands, can occur on freshwater wetlands on nearby Roebuck Plains and Anna Plains when water levels are suitable.

Red-necked Avocet, *Recurvirostra novaehollandiae*. Typically found in inland wetlands; small numbers occur with some regularity in Roebuck Bay, foraging on sheltered tidal flats near Crab Creek and joining flocks of Black-winged Stilt at high tide roosts. Occasionally numbers in the low hundreds have been observed (A.N. Boyle pers. obs.), but this has not yet happened when formal counts were being carried out.

Red-capped Plover, *Charadrius ruficapillus*. In dry conditions numbers on the Kimberley coast are augmented by birds from inland wetlands, leading to fluctuations in count totals. Nevertheless internationally significant numbers occur regularly on the shores of northern Roebuck Bay, Bush Point and Eighty-mile Beach, roosting with flocks of small migratory shorebirds such as Sand Plovers and Red-necked Stilts. Internationally significant numbers breed on the supra-tidal claypans of Roebuck Bay (Rogers *et al.* 2001).

Masked Lapwing, *Vanellus miles*. Largely a grassland species, the few records of this species at high tide roosts are a very small portion of the total local populations.

Australian Pratincole, *Stiltia isabella*. Occasionally encountered on the Kimberley coast, but this species occurs mainly on inland plains and wetlands.

Population changes

Relatively few shorebird surveys have been conducted along much of the Kimberley coast, and for most of the region we do not have an adequate history of data collection to assess whether shorebird populations are changing. However, counts have been repeated a number of times at the two most important sites, Eighty-mile Beach and Roebuck Bay.

Three complete surveys of Eighty-mile Beach have been carried out during the non-breeding season. Shorebird numbers observed in the most recent survey, in December 2008, differed substantially from those on previous surveys in October 1998 and November 2001, although all surveys were undertaken using the same methods, in the period between shorebird arrivals and the onset of wet season rains (Rogers *et al.* 2008). The differences between these surveys are summarised in Table 2. Most migratory species (10 of the 13 most numerous migrant species) had declined in numbers in 2008, the exceptions being species that also use freshwater wetlands (Common Greenshank and Red-necked Stint), and one (Sanderling) that forages on ocean beaches as well as tidal flats. Species which are typically restricted to tidal flats during the non-breeding season had apparently all declined, and for some species the decrease in numbers was dramatic, with 2008 counts being at least 50% lower than in 2001. In contrast, resident coastal species such as Australian Pied Oystercatcher had increased in numbers.

We cannot yet assess whether parallel declines in shorebird numbers have been occurring in Roebuck Bay, as the February-centred counts carried out in Roebuck Bay until 2000 are not comparable to the more reproducible November-centred counts carried out since

Table 2

Numbers of the most abundant coastal shorebirds species (regularly >500 birds per count) during complete summer counts of Eighty-mile Beach. Species that declined between 2001 and 2008 are italicised.

	17-18 Oct 98	12-13 Nov 01	10-12 Dec 08	2008 total as % of 1999- 2001 counts
Coastal Migrants				
<i>Grey Plover</i>	1,416	1,585	1,146	72.3%
<i>Greater Sand Plover</i>	63,482	64,584	22,885	35.4%
<i>Bar-tailed Godwit</i>	110,290	97,403	51,719	46.9%
<i>Eastern Curlew</i>	709	552	423	59.7%
<i>Terek Sandpiper</i>	7,989	9,820	4,628	47.1%
<i>Grey-tailed Tattler</i>	10,436	14,647	7,950	54.3%
Common Greenshank	1,738	2,432	2,534	104.2%
<i>Ruddy Turnstone</i>	3,480	1,649	2,433	69.9%
<i>Great Knot</i>	158,082	169,044	128,653	76.1%
<i>Red Knot</i>	24,891	29,679	23,123	77.9%
Sanderling	2,230	3,219	3,605	112.0%
Red-necked Stint	16,766	24,005	28,443	118.5%
<i>Curlew Sandpiper</i>	2,859	7,984	3,292	41.2%
Resident Shorebirds				
Australian Pied Oystercatcher	653	694	809	116.6%
Red-capped Plover	2,512	3,077	6,752	219.4%
Total coastal migrants	404,867	427,139	284,705	66.6%
Total Resident shorebirds	3,179	3,786	7,597	239.0%

2001; in addition, systematic counts of one of the most important roosts in the bay, Bush Point, did not begin until 2004. It is clear however, that the declines on Eighty-mile Beach have not been matched by corresponding increases in Roebuck Bay

Discussion

Taken as a whole, the Kimberley coast is an extraordinarily important region for shorebirds. It is used by over 3.7 million shorebirds, including 25 species which occur in the region in internationally significant numbers (*i.e.* > 1% of the flyway population). No other region in Australia, or indeed anywhere else in the East Asian Flyway, supports such large and diverse non-breeding populations (Bamford *et al.* 2008).

The total of 3.7 million shorebirds is somewhat skewed by three species (Oriental Plover, Little Curlew and Oriental Pratincole) which forage on grasslands rather than tidal flats; they were recorded in coastal surveys as they loaf on beaches of the Kimberley coast, exploiting the relatively cool microclimate of surf-dampened sand or mud to avoid thermal stress during mid-day heat. Whether these species are actually dependent on the Kimberley coast is debatable; they are certainly dependent on the near-coastal grasslands where they forage, but whether or not these sites would be exploited if there were not thermal refuges on nearby beaches is a question that has not been fully investigated. The availability of beach roosts may be of particular importance to Oriental Plover, which occurs in large numbers on the plains behind Eighty-mile Beach every year, and forages on bare and exposed plains which become especially hot during the day.

Even when these grassland species are excluded from consideration, the Kimberley coast ranks as the most important non-breeding area for shorebirds known in Australia and the East Asian – Australasian Flyway; it is used by over 649,000 shorebirds which forage in intertidal areas, including 22 species that occur in internationally significant numbers. Within the Kimberley region, the distribution of these birds is patchy, with over 90% of the coastal shorebirds occurring at just two sites: Eighty-mile Beach and Roebuck Bay. Both sites have enormous tidal flats which have been shown to have an abundant and diverse macrozoobenthos fauna, and therefore provide rich feeding grounds for shorebirds (Pepping *et al.* 1999a; Piersma *et al.* 2005)

The tidal flat systems surrounding Adele Island, Ashmore Reef and the Lacepede Islands are also important for some shorebird species, such as Pacific Golden Plover, Grey Plover, Lesser Sand Plover (Adele Island only), Grey-tailed Tattler, Ruddy Turnstone and Sanderling. In contrast, other species such as Black-tailed Godwit, Asian Dowitcher, Great Knot and Red Knot are relatively uncommon at the same sites. It is not known why the island sites are more attractive to some species than others, and benthic surveys may be needed to answer this question. We can put forward two hypotheses: (1) The coarse sand substrates surrounding the islands may be unsuitable for some shorebird species such as Black-tailed Godwit and Asian Dowitcher, which

in Roebuck Bay forage only in soft sediments (Rogers 1999); (2) Some species may have patchily distributed prey, and may therefore require very extensive tidal flats in order to increase their chances of locating profitable foraging areas. For example, Great and Red Knots feed mainly on bivalves which are swallowed whole, and tend to concentrate in patches where a recent spatfall has resulted in high densities of small bivalves with thin shells that are easily crushed in the gizzard (Rogers 1999).

No systematic ground counts of shorebirds have been carried out on the very long, and mostly remote stretch of coastline between the Dampier Peninsula and the Northern Territory. It is possible that more detailed surveying will reveal the presence of other small shorebird sites, and perhaps even some with internationally significant numbers of some species. However, aerial surveys of this coastline indicate that it is not inhabited by large numbers of shorebirds (Lane 1987, Kingsford *et al.* 2010, C.D. T. Minton and A.N. Boyle pers. comm.), and we can be confident that there are no further sites to be discovered which are as important to shorebirds as Roebuck Bay and Eighty-mile Beach.

The absence of shorebirds on much of the northern Kimberley coastline is not unexpected, as many of the shorelines are rocky and steep, without extensive tidal flats; in some regions extensive mangrove forests (Johnstone 1990) make intertidal areas of the Kimberley shoreline unsuitable for shorebirds. Moreover, the presence of extensive tidal flats does not necessarily mean that shorebirds will be present in large numbers. For example, relatively few shorebirds occur in King Sound (at the mouth of the Fitzroy River, Fig. 1), although it is only 150 km from Roebuck Bay and has even larger tidal flats. In November 1997, a survey of Doctor Creek, a site within King Sound containing about half of the most promising looking shorebird habitat in the sound, revealed the presence of only 1156 shorebirds (Hassell 1997). Anecdotal reports from a benthos-sampling expedition that travelled over much of the remaining tidal flat area in King Sound by hovercraft in July 1998 (Pepping *et al.* 1999b) indicated that still fewer shorebirds were present on the outer flats. The benthos surveys carried out by this team indicated that the benthic fauna in King Sound was depauperate: it was far less diverse and numerous than that in Roebuck Bay, with particularly low densities of polychaetes and bivalves. The low benthos abundance (and the resultant low abundance of shorebirds) was attributed to the tidal and freshwater scouring that occurs in this system, with huge tides (>11 m) reworking the sediments, causing high water turbidity and sweeping fine-grained sediment into the open ocean. In addition wet season flows from the Fitzroy River cause enormous salinity fluctuations in King Sound which are likely to be fatal to many benthic species (Pepping *et al.* 1999b).

The relatively low numbers of shorebirds in some sites in the Kimberly are not easily explained. For example, we remain puzzled by the low shorebird numbers found on the 130 km coastline between the Ord River and the Northern Territory border. Hassell *et al.* (2006) found only 924 shorebirds here in an aerial survey in November 2005, consistent with the low counts recorded on three other aerial surveys in 1985 (C D T Minton, pers. obs.), October 2008 and November 2009 (A N Boyle, pers. obs.),

and also with the low counts of shorebirds in the adjacent Northern Territory sections of Bonaparte Gulf reported by Chatto (2003). Why shorebird numbers should be low here is a mystery to us; from the air the habitat appears to be very suitable for shorebirds, with extensive tidal flats, and far less tidal scouring or freshwater influx than in King Sound.

It is clear that conservation of the majority of shorebirds along the Kimberley coast depends on protection of a relatively small number of sites. Fortunately, by world standards these sites face relatively few immediate threats and are in good condition. Protected by their isolation, they have never been threatened by processes that have caused deterioration or loss of many tidal flat habitats overseas, such as land reclamation, large-scale shorebird hunting, urbanisation or intensive harvesting of shellfish. In addition, the large tidal ranges of the Kimberley coast should help to buffer the tidal flats from area reduction if global warming should result in sea-level rises.

There are nevertheless some conservation concerns in Roebuck Bay. Nutrient enrichment in sections of the bay near to Broome township has resulted in increasingly frequent blooms of cyanobacteria; there are indications that this has already influenced benthos composition in the tidal flats and foraging behaviour of Bar-tailed Godwits has changed as a result (Estrella *et al.* 2011).

Disturbance of shorebirds at roosts on the northern beaches of Roebuck Bay is also of concern. Roost studies from 1997–2000 demonstrated that disturbance levels at these sites are high, with birds often undertaking energetically costly alarm flights to escape potential danger from birds of prey and humans. In 2000, disturbance levels were approaching the point at which energetic costs of disturbance on the northern beaches were too high to make foraging in northern Roebuck Bay profitable for shorebirds (Rogers *et al.* 2006c). Since then, disturbance levels on the northern beaches have been measured in 2005/06 (Rogers *et al.* 2006e) and 2007/08 (Sitters *et al.* 2009). These surveys indicated that disturbance levels had increased since 2000, and also suggested that shorebird numbers on the northern beaches of Roebuck Bay are declining during the dry season, when disturbance levels are high because of increased numbers of human visitors and birds of prey (especially Brahminy, Black and Whistling Kites, which may in turn be increasing in numbers on the northern beaches due to increased availability of fishing scraps from visitors). It is a worrying situation, especially as the human population of Broome continues to grow. Continued monitoring of disturbance is required, along with an assessment of whether existing conservation measures (mainly public education through signposting) are effective enough to control disturbance levels. The recently announced designation of Roebuck Bay as a Marine Park may be important in providing mechanisms to control the amount of human disturbance in the bay.

Both the nutrient enrichment and increased disturbance levels now observed in Roebuck Bay are indicative of the type of challenges that shorebirds may face in this site as Broome continues to grow. Other conservation issues that may become important in the future include increased pressure for coastal development near Broome (such as a proposed marina

near Broome Port), and increased shipping in the area, especially should a proposed LNG hub proceed. The environmental risks from increased shipping will need careful assessment and management, as the localised distribution of shorebirds on the Kimberley coast may make their populations very vulnerable to oil spills.

Although there is a need for continued vigilance, we believe the shorebird habitat on the Kimberley coast to be mostly in good condition. Nevertheless, there are indications that shorebird populations in the region may be declining. At Eighty-mile Beach, 10 of the 13 most numerous migrant species declined in numbers between 2001 and 2008, some declining to less than 50% of their previous levels. These differences between surveys are unlikely to have been caused by local movements of birds to sites outside the survey area, given the very large scale of complete Eighty-mile Beach counts (220 km of beach with no alternative roost habitats known). The shorebird declines are also unlikely to have been caused by local habitat changes to this near-pristine site. Rather, we think they are part of a flyway-wide phenomenon which has also caused serious declines in populations of migratory shorebirds in southern Australia (Gosbell and Clemens 2006), New Zealand (Southey 2009) and south-east Queensland (Wilson *et al.* in press).

The widespread nature of shorebird declines in non-breeding grounds of the East Asian – Australasian Flyway indicates that the causal factors lie outside the non-breeding areas. They are unlikely to have been driven by fluctuations in breeding success, given that the proportion of first year birds within North Western Australian and Victorian non-breeding flocks has shown no indication of persistent decline since the AWSG and the Victorian Wader Study Group began to record age-ratios systematically in the late 1990's (Rogers & Gosbell 2006; Minton *et al.* 2009). Instead, the declines are widely considered by shorebird biologists to be driven by loss of staging habitat used by shorebirds on migration. Enormous areas of tidal flats have been "reclaimed" (converted to land) on the Asian coast in the past 2–3 decades, including almost half of the tidal flats of the Yellow Sea, the most important region for staging shorebirds in our flyway (Barter 2002; Moores 2006; Bamford *et al.* 2008; Rogers *et al.* 2010). In some other flyways, deterioration or loss of staging areas has been shown to cause increased adult mortality and resultant population declines in shorebirds (e.g. Baker *et al.* 2004; Burton *et al.* 2006, van Gils *et al.* 2006, Kraan *et al.* 2010). Shorebird declines in the Asian – Australasian Flyway have not yet been studied to the same level of detail, but the same processes presumably occur.

The greatest conservation threats to the migratory shorebirds of the Kimberley coast probably lie overseas rather than in Australia, but that does not diminish our need to monitor the shorebird populations of the Kimberley coastline. Rather, it intensifies the need to conduct robust monitoring, as the data obtained are important as a barometer of the health of the entire flyway, and help to identify those species in most urgent need of conservation action. North Western Australia is also an ideal base for studies of the migration routes used by our shorebirds. A great deal has already been learned from banding studies (e.g. Minton *et al.* 2006, Rogers *et al.* 2010) and the recent development of geolocators and

satellite transmitters small enough to be carried by migrating shorebirds (e.g. Clark *et al.* 2010) will further improve our capacity to identify those staging areas in greatest need of protection. Finally, we must not become complacent about conservation of our shorebirds on a more local scale; as economic development proceeds in the Kimberley, and towns such as Broome continue to grow, it will be important to ensure that the shorebird sites of the Kimberley remain adequately protected.

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Monitoring of humpback whales in the Pender Bay, Kimberley region, Western Australia

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Abstract

Information and learnings from two years of independent and shore-based humpback whale (*Megaptera novaeangliae*) surveys in the remote Kimberley region are presented. Systematic shore-based surveys were undertaken in 2009 and 2010 from the cliff top on the southern part of Pender Bay, Dampier Peninsula, Kimberley region, WA from the Two Moons Whale and Marine Research Base. The humpback whales use Pender Bay for a variety of purposes including calving, breeding, feeding (inferred), resting and staging. The results show the peak of the whale season to be in August with a relatively sharp increase in whale numbers occurring from mid July through to early August with whale numbers slowly decreasing from the end of August through to mid November. The whale numbers were higher in 2009 than 2010 and a range of environmental and meteorological variables have been compared to elucidate any trends. Mothers and calves predominated in the bay in September and October when the relative proportion of calves increased, indicating that Pender Bay was being used as a resting, feeding, calving and staging area. The ongoing challenge of monitoring humpback whales in this isolated part of the Kimberley is to manage the interplay between the availability of whale observers, an isolated location along the Kimberley coast and the amount of logistic support required to keep a field team in operation for the duration of the season which stretches from early June to mid November. We have therefore developed a pragmatic sampling technique, maximising the observer effort based on an average four person team on the cliff top operating five hours per day.

Keywords: humpback whale, seasonal variability, sea surface temperature, meteorological variables, whale behaviours, observer methodology

Introduction

Humpback whales (*Megaptera novaeangliae*) have long been known to migrate along the WA coast (Hedley *et al.* 2009); however, it has only recently become apparent, the comparatively large size of the population and the importance of the Kimberley region for this west coast Group IV population of humpback whales (Jenner *et al.* 2001). Pender Bay was previously known as a humpback whale staging area for the southerly migration commencing approximately mid-September, however the information recently presented by McKay & Thiele (2008), Double *et al.* (2010) and this study, further suggest that the area is significant as a calving, feeding (inferred by us), breeding and resting area as well as a major staging area for the southern migration which commences in mid-late September.

The challenge of visual fixed point monitoring of marine mega fauna in such a remote location requires a permanent observation point to be manned on an ongoing basis with humpback whales arriving early June and departing mid November from this locality each year. A lack of long term quantitative baseline studies for humpback whales in this region necessitates the need to establish such a monitoring program with some urgency based on the likely impacts of: (1) climate change and in particular rising water temperatures and changed primary productivity effects; (2) increased human usage of this coastline; and (3) the natural recovery of the population post the ban on commercial whaling.

A simple fixed point survey technique has been developed which can be implemented through mainly volunteer observers to ensure a rapid census approach to quantifying the relative numbers of whales in the bay each year. The purpose of this paper is to draw attention to this semi-quantitative study, the methodologies being

used and the large numbers of humpback whales utilising this part of the Kimberley coast. It is suggested that this type of study should form the basis, along with other recent surveys of humpback whales in the region using aerial, boat and underwater acoustics of an integrated long-term baseline monitoring of relative whale numbers and behaviours based on inter-annual and major climatic events such as ENSO and the Indian Ocean Dipole.

Aims

- To monitor the relative abundance of the Group IV population of humpback whales in the Pender Bay region of the Kimberley, WA, as part of the annual south-north-south migration along the coast.
- To characterise the different whale behaviours and usage of the Bay for activities such as resting, breeding, calving, staging, feeding etc.
- To develop a survey method for isolated regions which, as a result, have a heavy reliance on a largely volunteer observing effort.

Methods

Study Site

Pender Bay is located at 122 deg 38'E 16 deg 45'S on the north western side of the Dampier Peninsula, approximately 170 km north of Broome in WA (Fig. 1). The Bay faces in a NW direction with a gently sloping seafloor with an average depth of 12–15 m. Prominent landmarks include Perpendicular Head, Chimney Rocks, Woodhouse Rocks, Bell Point and Cape Borda. These fixed landmarks were utilised to assist with whale offshore distance predictions. Kelk Creek flows into the Bay with freshwater inflows mainly during the wet season periods. It was noted however that in July 2010 unseasonal dry season rains caused a major discharge

event into the Bay bringing in terrestrial detritus into the Bay and clouding the water for a 3–4 weeks.

The whale observing platform (concrete survey pad) is on the cliff top which forms the southern boundary to the Bay located at 122 36.546E 16 45.939S (GPS fix), 30 m above MSL and approximately 1 km west of the *Two Moons Whale & Marine Research Station* (Fig. 1). This region forms the far northern part of the Canning Coastal Bioregion. Tides are semi-diurnal with a maximum range of 9 m during Spring Tide periods. The region can become isolated during wet season monsoonal conditions but is easily accessible from Broome during the dry season periods. Cyclones (normally Category 1 or 2) frequent the area during wet seasons and are mainly associated with major La Nina climatic events. "Whale season" in the Bay typically spans from the second week in June until early November when the last mothers and calves depart the Bay. There has been historically little oceanographic work or marine habitat studies undertaken in Pender Bay, however an automatic Meteorological Station was established by the State Government in 2009 on the Lacepede Islands in a WSW direction from Pender Bay (Fig. 1) and this provided detailed continuous meteorological measurements coincident with the study. Based on its location and the height of the observing platform on the cliff top 30 m above MSL, this geographic location is ideally positioned to capture the inshore S – N – S migration of the humpbacks as part of their annual migration.

Survey technique

The survey was conducted over a two year period, starting on the 2nd of August 2009 and going until the 4th of November 2009, then starting on the 10th of June and running until the 15th of November in 2010. The key to the survey methodology is simplicity and reproducibility, noting that fully quantitative surveys of whales are very challenging (Noad *et al.*, in press.). To ensure consistency, a qualified *lead scientist* was nominated to ensure that recording methodologies and timings were strictly adhered to. Four or five other people supported the lead scientist in making and recording the whale observations. Data were immediately entered into a spreadsheet at the conclusion of each counting period by the lead scientist to ensure consistency. Whale counts were made from the cliff top location, with each observed whale behaviour recorded along with offshore distance estimations.

Whale behaviours were further standardised in 2010 based on the experiences from the 2009 survey to ensure that observers distinguished/ recorded the main behavioural types as follows: *breaching*, *blowing*, *lobtailing*, *pectoral slapping*, *logging* (surface resting), *surface travelling*, *chin slapping*, *spy hopping*, *blow and dive* (blow at the surface followed by a deep dive), *bull run* (a pod of males moving to intercept a female), *other* (any less common behaviour not listed above).

With a 190 degree field of view from the survey location on the cliff top two observers used their "naked eyes" in the left hand (LH) and right hand (RH) quadrants out from the cliff top respectively, with another two observers utilising binoculars in the LH and RH quadrants beyond the naked eye field of view (Fig.



Figure 1. Location of Pender Bay, Dampier Peninsula, WA. Inset, the location of the Study Site [whale observing platform] and the Two Moons Whale & Marine Research Base [Base map courtesy Google Earth].

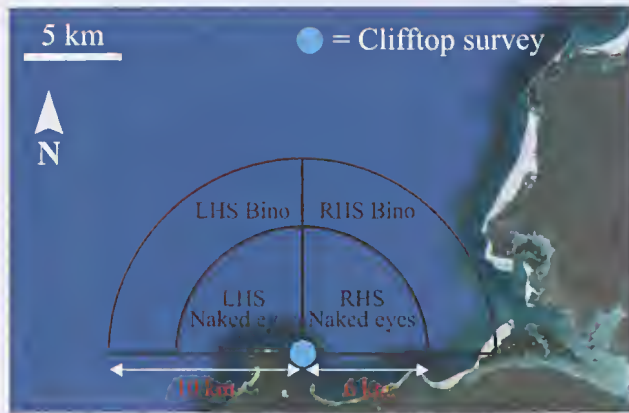


Figure 2. Viewing areas [180 degrees east and west of arc] from the Pender Bay cliff top survey location [Base map courtesy Google Earth].

2), which is normally 6–7 km offshore based on known fixed-points in the Bay and boat-based GPS distance surveys. If a fifth observer was present, they were tasked with following specific pods of whales and recording detailed behaviours and tracks. Counting was undertaken for five minutes commencing at 0700 each day and was then followed by a ten minute break when the field data from the log sheets from the individual observers was entered into the master spreadsheet by the lead scientist. Another five minute counting period was then instigated, followed by another ten minute break and so on. This continued for five hours at a time. This represented 100 minutes of sampling per person per day (actually a total of 400 minutes per day based on the four observer team) with strict timings between observation periods and rest times maintained. The observing team in operation as part of the cliff top survey are shown in Figure 3 based at 16 45.939S 122 36.546E and at 30 m above MSL.

Whilst most counting was undertaken in the morning, from 0700–0920, and Lunch time periods, from 0930–1205, we also undertook afternoon sampling from 1400–1705 on several occasions through the season to enable a time of day sampling comparison. Laminated field log sheets were utilised by all observers and at the end of every five minute period, the data were entered directly into the Excel spreadsheet on a field laptop computer where all related information such as visibility, number of observers, presence or absence of boats and local meteorological conditions were recorded.

Whale sightings and behaviours were recorded separately by each of the naked eye observers on the field sheets. Where individual whales were clearly reappearing, they were only counted once during any five minute recording period. The frequency of the different whale behaviours was also recorded by both of the naked eye observers during the 5 minute scanning periods. The observers scanning the horizon with the binoculars only recorded the number of whale sightings and not the type of whale behaviours. Splashes in the far distance were always counted as separate sightings as we could not distinguish individual whales within a pod in the six to ten kilometre range, as seen by the observers using the binoculars.

Several local landmarks were utilised to train observers to estimate whale distances offshore as well as offshore distance surveys being undertaken by boat and photographed from the cliff top to ensure that the distance estimates were consistent between days/weeks/years/observers.

Volunteers were all trained in the survey technique on the cliff top for three days prior to being allowed to participate in the whale observing team and were carefully monitored by the lead scientist ensuring as high a consistency of approach as possible.



Figure 3. Whale observation team in operation on the cliff top at Pender Bay at 16 45.939S 122 36.546E at 30m above MSL [Photo S. Blake].

Meteorological data were sourced from several locations in the region: Cygnet Bay, Lombadina (commencing February 2010), Lacepede Islands and North Head which included air temperature, mean sea level pressure (MSLP) and wind speed. These data were then compared with the humpback whale sightings and behaviours for that particular day. In addition, sightings of vessels in the Bay were recorded with a standardised key.

Tides

Data from two tide stations, Red Bluff to the south, and Karrakatta (Cape Leveque) to the north of Pender Bay were averaged to ensure a more accurate representation of the timing, height and state of high tide-low tide periods throughout the sampling period. High and low tide periods were defined as 40 minutes either side of the calculated average from the two tidal stations. The incoming and outgoing tides were defined as times falling outside that of the high and low tide categories. The averaging between these two tide stations was validated on several occasions and in all cases were found to be within five minutes of the actual observed tide. This tidal averaging approach was utilised for both 2009 and 2010 data.

Satellite sea surface temperature and Chlorophyll-a

Satellite data from both the Aqua and Terra satellites were analysed with a mean sea surface temperature (SST) and chlorophyll-a value being averaged for each day as long as it was within the tolerances of the validation algorithms for a 10km x 10km region of Pender Bay. These values were then graphed across the two years of humpback whale observations (2009 and 2010) and also for 2008, (a strong La Nina period) the year before our survey commenced to enable comparison.

Statistical analysis

No high end statistical analyses were performed on the data as they did not meet the independence assumption of the most common forms of statistical analysis. In order to account for the dependence in the data, some form of Time Series Analysis or a Repeated Measure Analysis would be required. However, as the data is not currently suitable for high end statistical analysis, we therefore undertook some basic comparative and descriptive statistics. The main purpose of this paper is therefore to highlight any trends observed over the two years of the survey.

As the frequency of occurrence of the different whale behaviours observed was largely influenced by the actual number of whales present in the Bay, all behavioural data has been normalised as a proportion of whales sighted.

Some basic descriptive statistics were undertaken on the 2009 data and the Excel spreadsheet was refined and slightly modified for the 2010 survey period to ensure that statistical analysis were planned prior to undertaking the 2010 sampling. It was found that entering the data directly into the Excel spreadsheet in the field (as per the 2010 survey) was far more streamlined than simply entering the observation data into field log sheets (2009) and then re-entering the

information into a spreadsheet. Whilst the completion of the spreadsheet creates more work in the field on site, it prevents the duplication of effort in transposing data in the lab on return and we believe reduces the chance of data entry errors and ensures a more consistent approach to field data completion as questions and queries that the lead scientist may have of the observers can be addressed immediately.

Possible errors identified in the sampling include:

- Double counts of the same whales. There was the possibility that whales could move between the different quadrants during the 5 minute period. This was negated by the observers notifying each other if whales which, had already been counted, were passing into another's quadrant during the 5 minutes.
- Non observation of whales which were present. This occurred when an observer was looking in another direction within the quadrant of interest when a whale appeared; this was mainly manifested during the peak of the season when multiple whales (up to 91) would appear within the five minute period. This error was reduced by having an additional observer present and by having observers inform each other if a whale was spotted by one observer and not the other.
- Inaccurate distance estimates. Without the use of distance estimation devices, distance estimation remains subjective, however all observers were trained in distance estimation through the use of known distances to natural landmarks.
- Variability in observer effort. Surveys were predominantly conducted with four observers however there were times when observers were not available, in which case two or three observers were present. This was accounted for by standardising the data for observer effort by dividing the number of whale sightings by the number of observers present.
- Pseudo-replication of whales. As the sampling periods were close together (10 minutes apart) sometimes we recounted whales between the different five minute sampling periods. Multiple behavioural readings were often taken from the same whales. Unfortunately little could be done to account for this without doing a repeated measure or time series analysis to account for the dependence inherent in most cetacean studies involving behavioural monitoring.

Results and Findings

Numbers of whales and timing

As the 2009 whale survey was not instigated until the 2nd of August we do not know for sure as to when the first whales arrived in Pender Bay, however sightings off Broome indicate that the whales were arriving in early June and the last whale was seen in the bay on the 4th of November. In 2010 the first whale was spotted on the western side of Pender Bay on the 11th of June with the final whale being seen in the bay on the 9th of November,

however, we observed that humpback whales were still present further offshore at the Lacepede Islands, as late as mid November.

The mean number of whale sightings per person was higher in 2009 than in 2010 with 3.85 ± 0.12 and 1.52 ± 0.04 whale sightings per person respectively (Table 1), which represents a 60% decrease in the number of whale sightings over the two years. This decrease was still evident even when the years were adjusted for the same August–November time period.

After the August peak in 2009, the mean whale sightings decreased markedly in September and then more gradually over the September to November period (Table 1). In 2010, after the arrival of the first whale, whale sightings increased rapidly in late July and peaked in August with a mean of 3.83 ± 0.08 ; this was then followed by a subsequent decrease in September (2.41 ± 0.09) followed by a gradual decline over October and November (Table 1).

The proportion of mothers with calves increased greatly after the peak in August for both 2009 and 2010 (Fig. 4), with the birth of two calves and several mating attempts (including mothers with calves) being witnessed during the late September to early November period. We can see from Figure 4 that in 2009 the mean percentage of calves increased from 1.07 ± 0.15 in August to 4.17 ± 0.62 in October before dropping off completely by November. That trend was the same for 2010 with the mean number of calves reaching 8.35 ± 0.46 in September and dropping off drastically in November. It was also

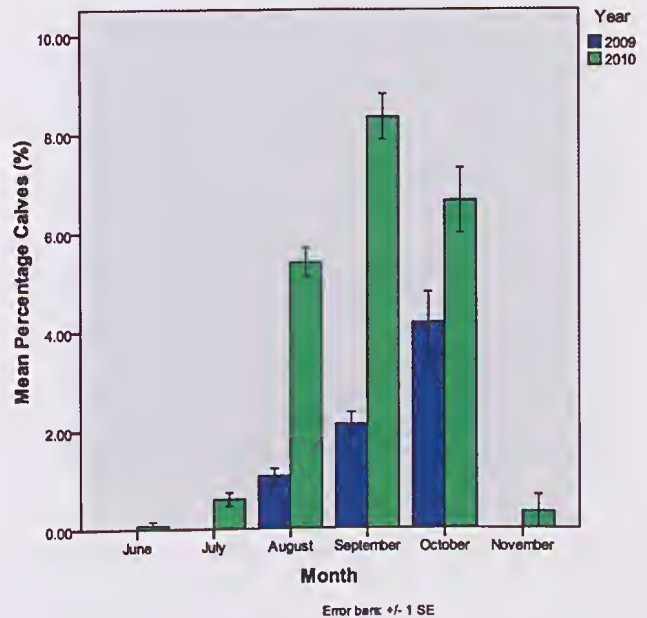


Figure 4. The mean percentage of calves present in each month for the 2009 and 2010 whale seasons.

noted that there were a greater percentage of calves present overall during the 2010 season, almost double that of 2009.

During 2009 we noticed that there was a decrease in the number of whale sightings during the middle of the day, which was referred to as “whale siesta time”. This decrease is clearly seen in Table 1 where the mean number of whale sightings drops from 4.21 ± 0.21 in the morning to 3.45 ± 0.14 at lunch before increasing to 4.13 ± 0.28 in the afternoon period. This “whale siesta time” was not as evident during the 2010 season, with little difference present between the different times of day, however behaviours were observed to change.

Sea Surface Temperature and Chlorophyll-a

By plotting the sea surface temperature (SST) with the mean number of whale sightings (Figs. 5 and 6) we can see that there is a negative relationship present, this relationship becomes more apparent with the 2010 data (Fig. 6) with the lowest SST corresponding to the peak in the whale season. From this we can see that the peak in the whale season occurs when the SST is in the range of $26.7\text{--}27.9^\circ\text{C}$.

Chlorophyll-a, used as a proxy of the regions surface waters primary productivity, appeared to have an inverse relationship with SST, with the peaks of primary productivity generally corresponding to the decrease in the regions SST in 2008, 2009 and 2010 (Fig. 7). The chlorophyll-a concentrations also appear to be slightly offset with the peak of productivity occurring just before the start of the whale season, as shown in Figure 8.

A slight elevation in the SST was observed during 2009 and 2010 compared to 2008 with an increase in the variability of both the SST and chlorophyll-a readings in 2009 and 2010 when compared with 2008, a La Nina year (Fig. 7). Winter SSTs were noticeably lower in mid 2008

Table 1

Descriptive statistics of the normalised whale sightings for each of the months of the 2009 and 2010 whale seasons.

Year	Month	N	Min.	Max.	Mean	SE
2009	August	559	0	28.33	6.63	0.22
	September	504	0	8.60	2.35	0.08
	October	275	0	5.75	1.47	0.08
	November	39	0	1.00	0.13	0.05
	Overall	1377	0	28.33	3.85	0.12
	Time of Day					
	Morning	554	0	28.33	4.21	0.21
	Lunch	642	0	26.62	3.45	0.15
	Afternoon	181	0	18.50	4.13	0.28
2010	Month					
	June	437	0	0.60	0.01	0.00
	July	560	0	6.50	0.98	0.06
	August	509	0	10.00	3.83	0.08
	September	469	0	11.50	2.41	0.09
	October	441	0	3.25	0.54	0.04
	November	147	0	1.50	0.07	0.02
	Overall	2563	0	11.50	1.52	0.04
	Time of Day					
	Morning	1165	0	11.50	1.52	0.06
	Lunch	1062	0	9.25	1.53	0.06
	Afternoon	336	0	8.50	1.44	0.10

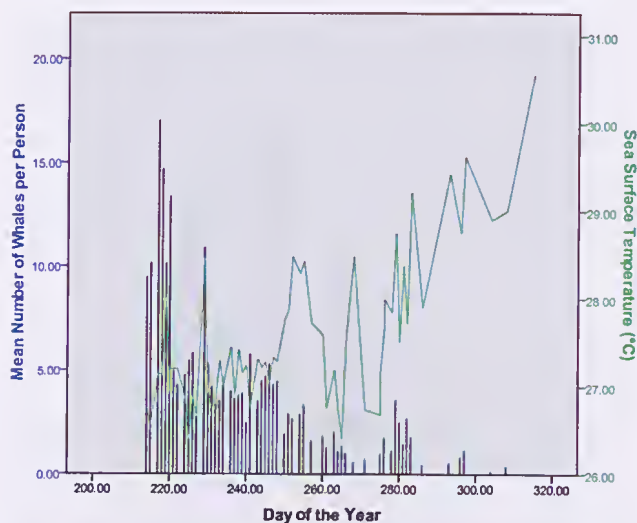


Figure 5. Mean number of whales normalised for viewing effort compared with sea surface temperature over 2009.

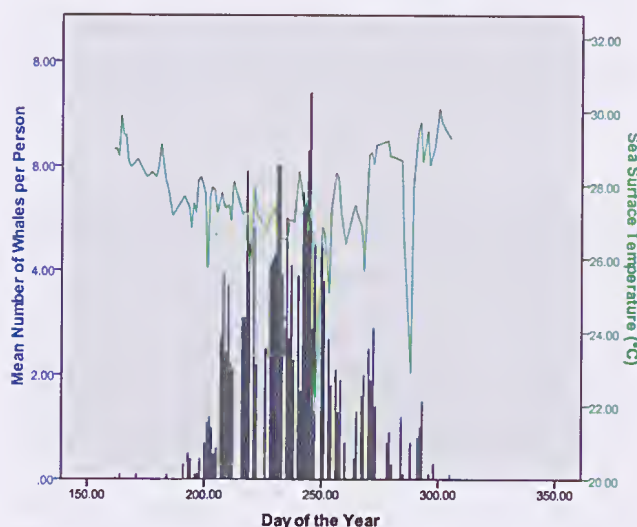


Figure 6. Mean number of whales normalised for viewing effort compared with sea surface temperature over 2010.

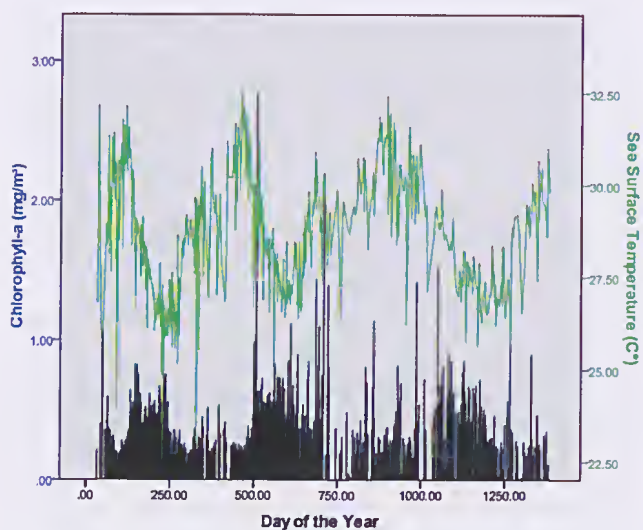


Figure 7. Mean chlorophyll-a concentrations and sea surface temperatures for Pender Bay over 2008, 2009 and 2010.

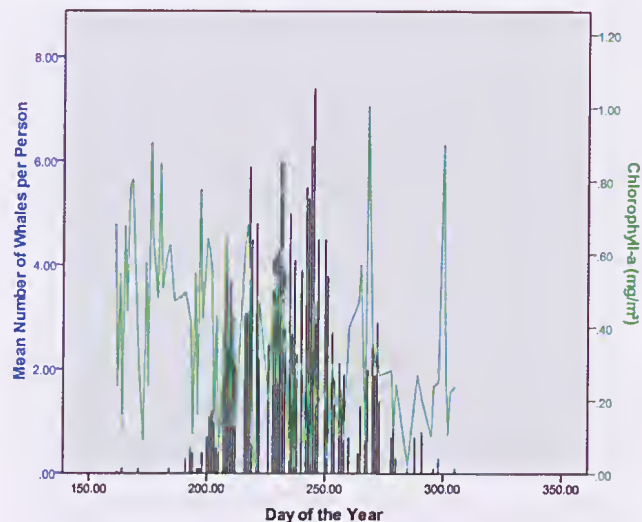


Figure 8. Mean number of whales normalised for viewing effort compared with chlorophyll-a concentrations over 2010.

coincident with the 'whale season' when compared to 2009 and 2010 (Fig. 7). The chlorophyll-a signature was particularly well defined for 2008 (La Nina year) when compared with 2009 and especially 2010. Similar seasonal and inter-annual variability trends in both SST and chlorophyll-a have been observed in the Camden Sound companion dataset where low winter SSTs (26–27.5°C) coincided with high numbers of whales observed in the region in 2008 (Blake, unpublished data).

Meteorological factors

Weak negative trends were observed between the number of whale sightings and North Head air temperature ($R=0.345$) and wind speed ($R=0.152$), Lacepede Island air temperature ($R=0.519$) and wind speed ($R=0.155$) with weak positive trends observed with both North Head and Lacepede Island MSLP ($R=0.443$ and 0.400 respectively) for 2009 (Figures 9–14). These trends become less clear during 2010 with little to no trends apparent between the whale sightings and North Head air temperature ($R=0.100$), MSLP ($R=0.063$), wind speed ($R=0.190$) and Lacepede Island air temperature ($R=0.095$), MSLP ($R=0.055$) and wind speed ($R=0.122$) (Figures 15–20).

The sea state, measured by the Beaufort wind scale, appeared to directly correlate with the mean number of whale sightings (Fig. 21). On days where the Beaufort wind scale was zero (very calm and still conditions) the mean number of whale sightings per person was greatest with 2.28 ± 0.09 sightings, this decreased linearly with no whales being sighted when the sea state had reached Beaufort scale 6 (large waves forming white caps with some sea spray), however those rough sea conditions were only represented by 4 sampling periods.

In addition to the sea state, the visibility also directly impacted on the number of whale sightings, with a combination of wind speed, sea state, salt spray and atmospheric haze all impacting on how well the observers could see across the Bay (Fig. 22).

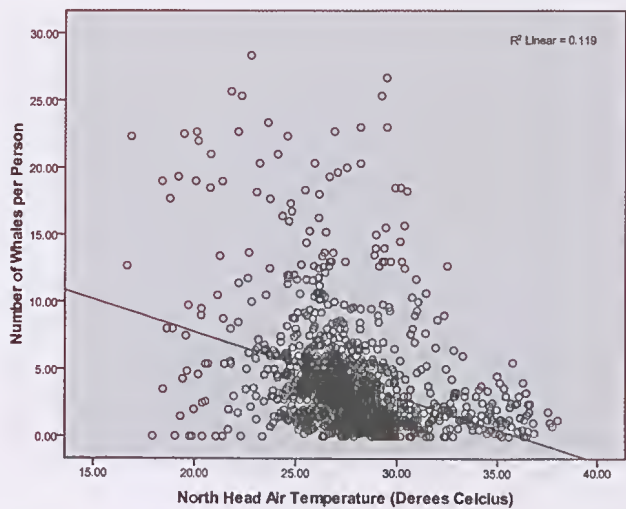


Figure 9. Scatter plot of number of whales normalised for viewing effort against the North Head air temperature with corresponding trend line for 2009.

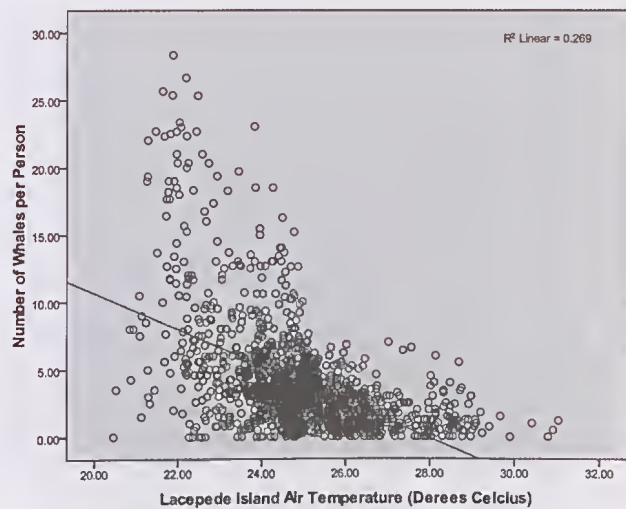


Figure 12. Scatter plot of number of whales normalised for viewing effort against the Lacepede Islands air temperature with corresponding trend line for 2009.

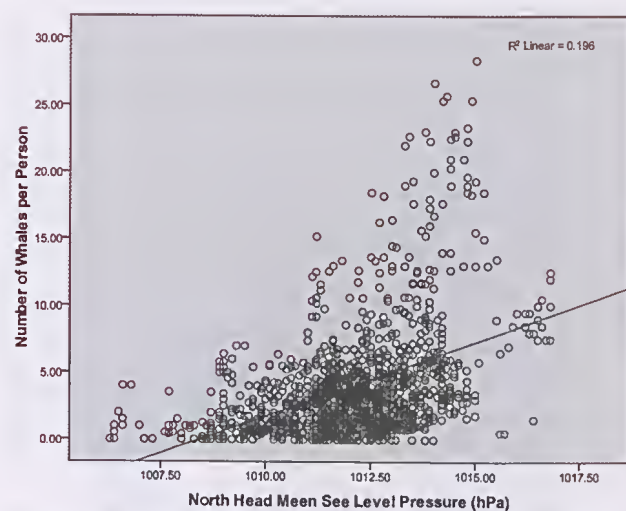


Figure 10. Scatter plot of number of whales normalised for viewing effort against the North Head MSLP with corresponding trend line for 2009.

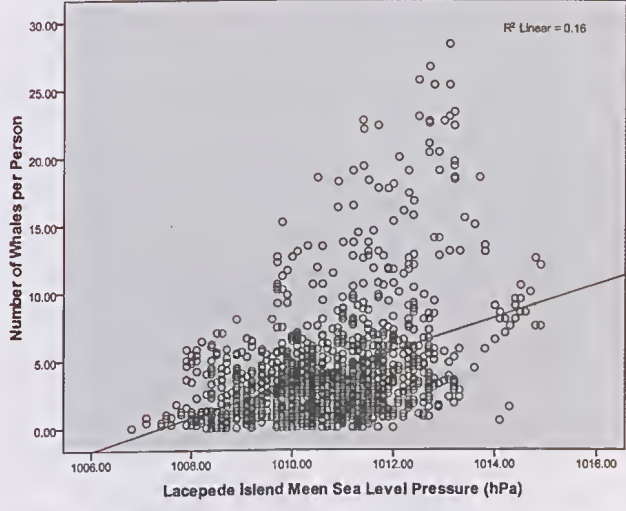


Figure 13. Scatter plot of number of whales normalised for viewing effort against the Lacepede Island MSLP with corresponding trend line for 2009.

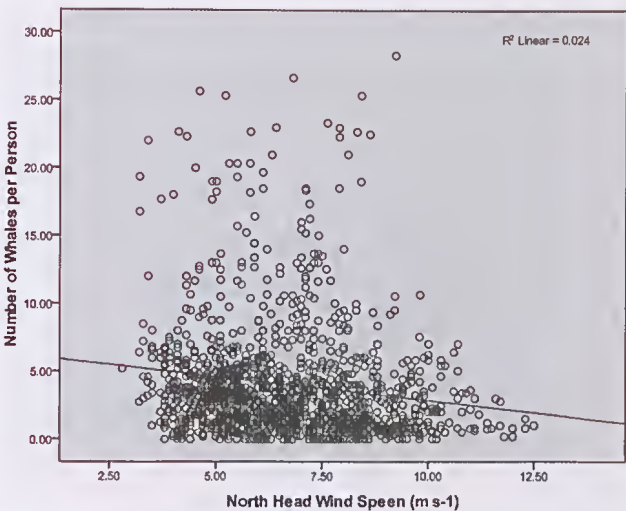


Figure 11. Scatter plot of number of whales normalised for viewing effort against the North Head wind speed with corresponding trend line for 2009.

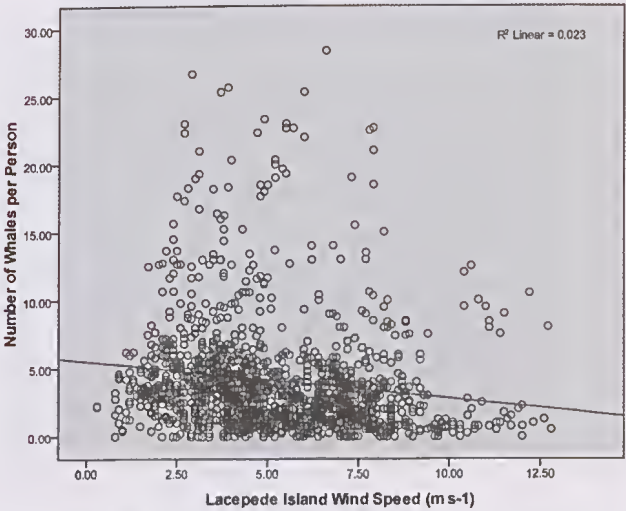


Figure 14. Scatter plot of number of whales normalised for viewing effort against the Lacepede Island wind speed with corresponding trend line for 2009.

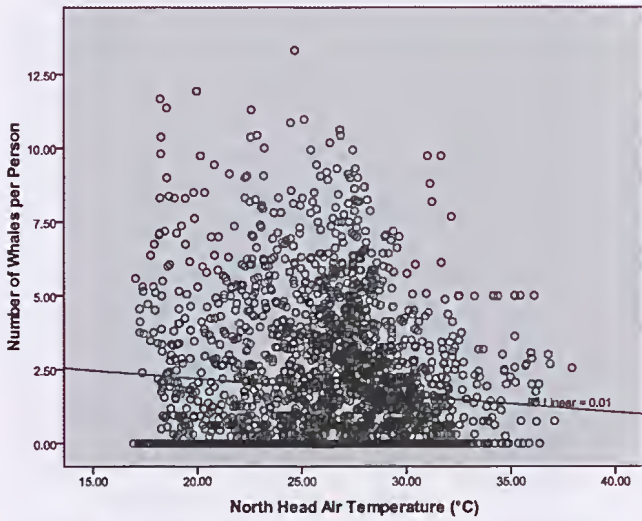


Figure 15. Scatter plot of number of whales normalised for viewing effort against the North Head air temperature with corresponding trend line for 2010.

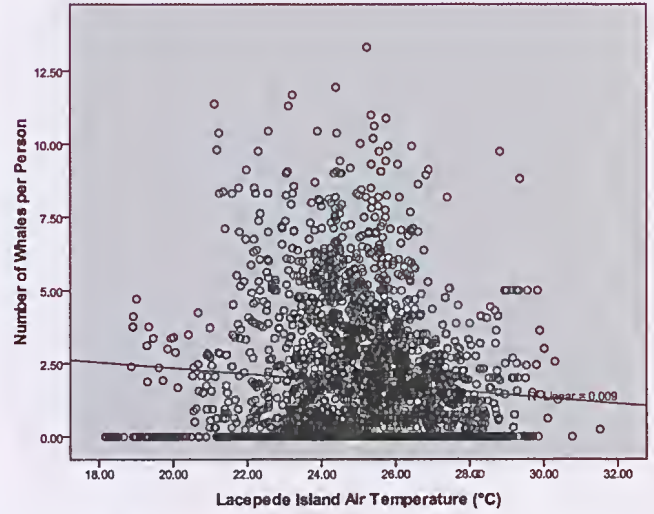


Figure 18. Scatter plot of number of whales normalised for viewing effort against the Lacepede Island air temperature with corresponding trend line for 2010.

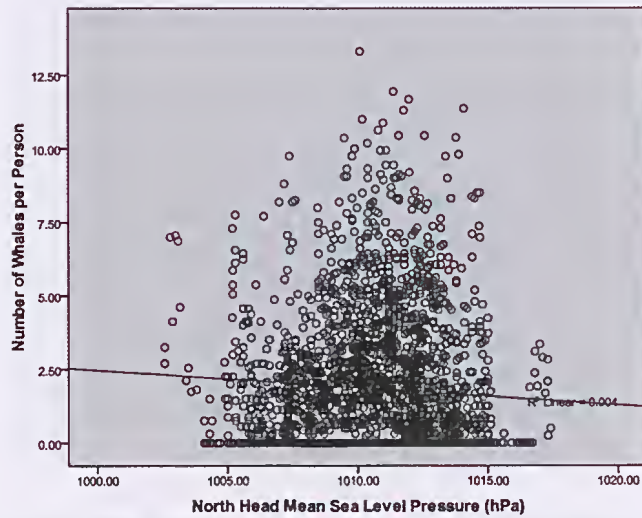


Figure 16. Scatter plot of number of whales normalised for viewing effort against the North Head MSLP with corresponding trend line for 2010.

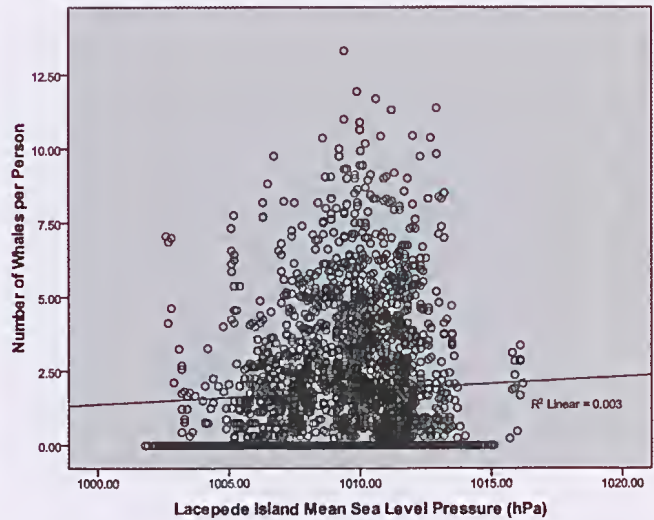


Figure 19. Scatter plot of number of whales normalised for viewing effort against the Lacepede Island MSLP with corresponding trend line for 2010.

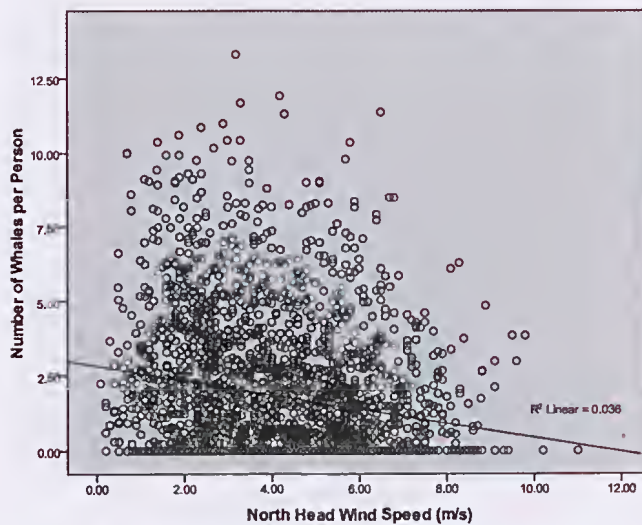


Figure 17. Scatter plot of number of whales normalised for viewing effort against the North Head wind speed with corresponding trend line for 2010.

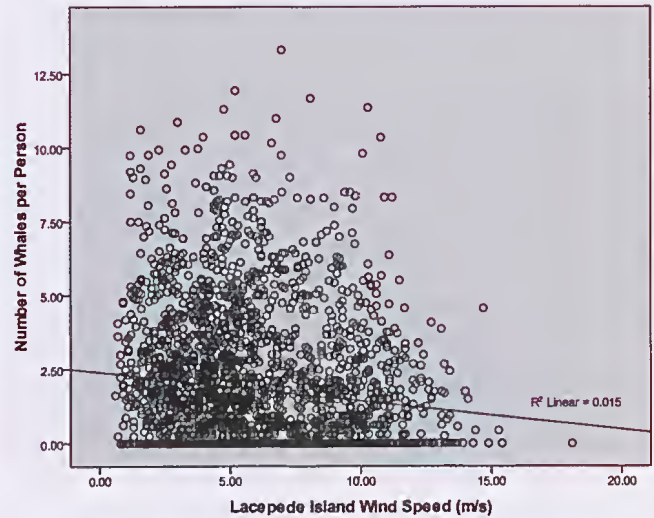


Figure 20. Scatter plot of number of whales normalised for viewing effort against the Lacepede Island wind speed with corresponding trend line for 2010.

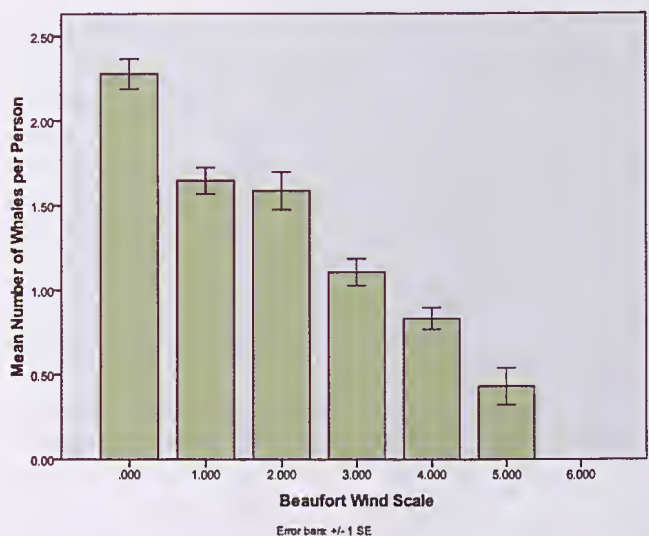


Figure 21. Mean number of whales normalised for viewing effort against the Beaufort wind scale for 2010.

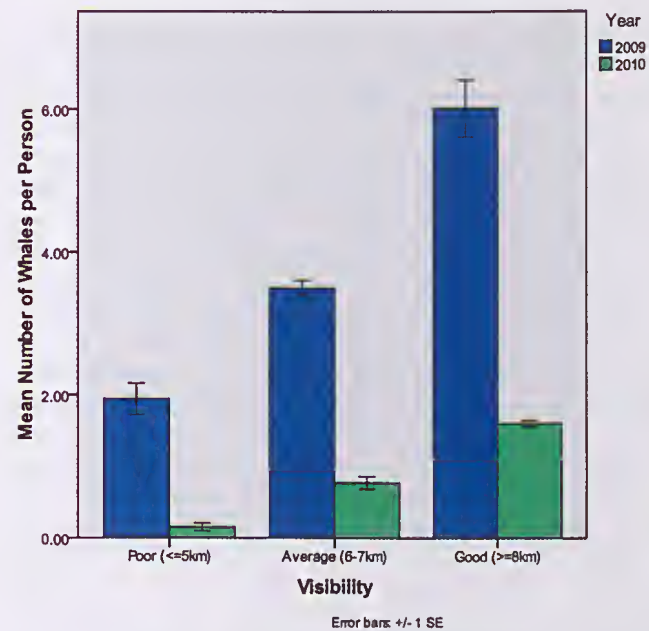


Figure 22. Mean number of whales normalised for viewing effort against visibility in 2009 and 2010.

Tides

It was observed that mothers and calves would drift in and out of the bay with the changing tides though no clear trend was apparent between the mean number of whale sightings and the state of the tide, apart from an increased number of sightings on an incoming tide in 2009 (Fig. 23). When viewed in the broader context of spring and neap tides there is a consistent trend in both 2009 and 2010 for a relative increase in whale sightings during neap tides and a relative decrease during springs (Fig. 24). This represents a 51% difference between neap and spring tides in 2009 with whale sightings decreasing from 4.75 ± 0.22 during neap tides to 3.14 ± 0.10 during springs, and a 41% difference in 2010 with the whale sightings changing from 1.80 ± 0.06 on neap tides to 1.29 ± 0.05 during springs.

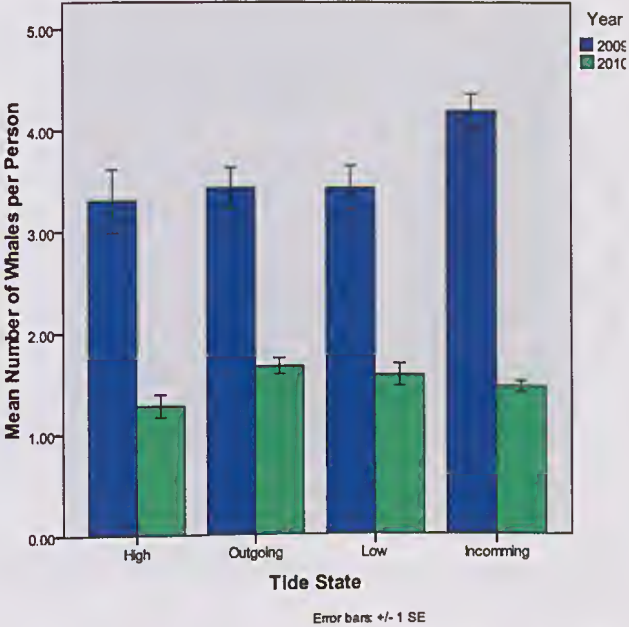


Figure 23. Mean number of whales normalised for viewing effort in different tide states for 2009 and 2010.

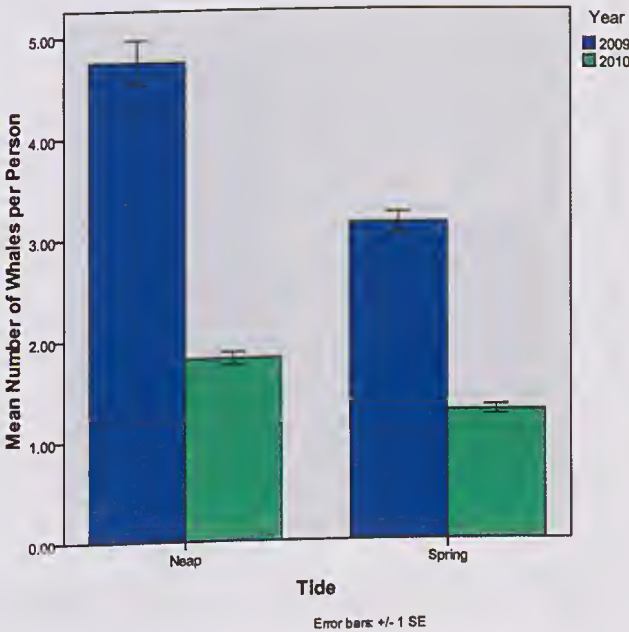


Figure 24. Mean number of whales normalised for viewing effort during neap and spring tides for 2009 and 2010.

Boats

As many as eight boats were observed utilising the bay during the 5 minute counting period, consisting to a large extent of local fishermen in small boats, however, larger vessels along with a few sailing yachts also frequented the bay. Boat numbers decreased rapidly in the bay in response to an increase in the sea state (measured as the Beaufort wind scale (Fig. 25)) and corresponding wind speeds, with the number of whale sightings following the same trend (Fig. 21). Whale sightings when boats were present, were higher in both 2009 and 2010 with a mean number of sightings per

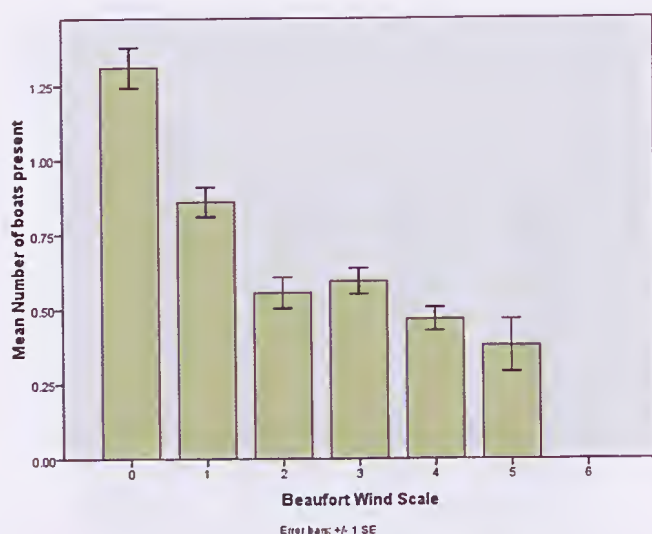


Figure 25. Mean number of boats present against the Beaufort wind scale for 2010.

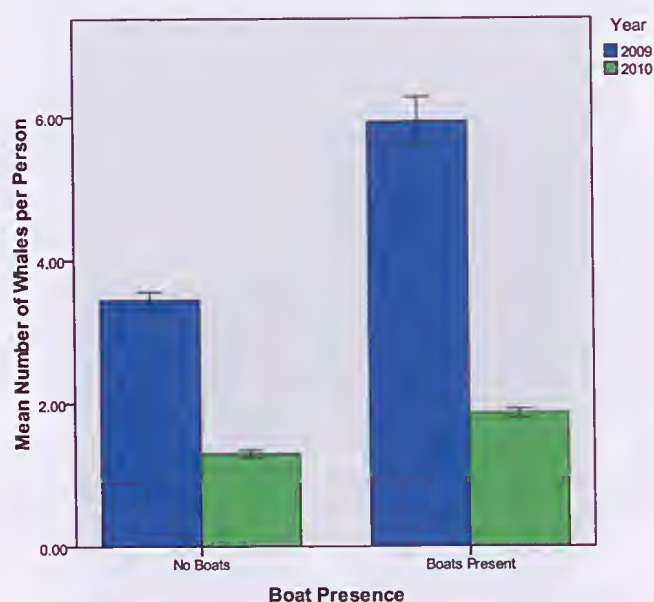


Figure 26. Mean number of whales normalised for viewing effort in the presence and absence of boats for 2009 and 2010.

person of 5.92 ± 0.34 and 1.85 ± 0.06 respectively. When boats were absent, the mean number of sightings per person was lower with 3.34 ± 0.12 in 2009 and 1.28 ± 0.05 in 2010 (Fig. 26).

Whale behaviours

Humpback whale calving, breeding, feeding, resting and associated staging behaviours were all observed in Pender Bay over the two years of monitoring. Overall, the types of whale behaviours remained constant through the season with breaching and blowing behaviours being the most frequently sighted; but also being those most easily seen from the cliff during poor visibility and rough seas.

The time of day appeared to influence the behaviours, in particular breaching, blowing, and surface travelling (Fig. 27). There was a decrease in the proportion of whales blowing around the middle of the day, with the mean proportion of sightings dropping from 0.25 ± 0.01 in the morning, before increasing again in the afternoon to 0.32 ± 0.02 . Breaching remained similar during the morning and lunch periods (both 0.09 ± 0.01); it however decreased to 0.04 ± 0.01 in the afternoon. Surface travelling also showed an increase in the mean proportion of sightings during the lunch period, increasing to 0.06 ± 0.01 from 0.05 ± 0.00 in the morning and decreasing to 0.03 ± 0.01 .

Changes to the whales' behaviours were also observed coincident with the presence of boats in the Bay, as seen in Figure 28. While boats were present, blowing, pectoral slapping, logging, surface travelling, blow diving and other behaviours all increased while breaching showed a slight decrease.

Discussion

The timing of the whale season was similar across both years of the survey with the whales arriving mid June, their numbers peaking in August before dropping off by early November. Our findings were consistent with those from the underwater noise loggers deployed by Curtin University for the same time period at James Price Point (Gavrilov and McCauley, 2010).

The mean number of whale sightings however was not consistent, with a 60% decrease occurring between 2009 and 2010. Research conducted by McKay & Thiele (2008) in the same area also noted variability in the number of whale sightings between the different years in Pender Bay. We postulate that this variability may partly be in response to the El Nino Southern Oscillation phenomena with associated possible Indian Ocean Dipole effects influencing the broad seasonal patterns of SST and chlorophyll-a concentrations. In order to determine if this is correct however, we would require additional years of monitoring and ideally have thermistors deployed along the edge of the continental shelf and also in a cross shelf pattern out from regions such as Camden Sound, Pender Bay and the southern part of Eighty Mile Beach.

We also experienced uncharacteristic "dry season" heavy rains during July 2010, which resulted in a large injection of red mud and freshwater from Kelk Creek which persisted in the bay for several weeks. We believe that this influx of turbid freshwater may also have impacted the number of whale sightings during that time. A large *Trichodesmium sp.* bloom was observed in the Bay in early September 2010.

A worldwide study of the effects of SST on the wintering areas of Humpback Whales revealed that in all areas where whales migrate during the winter, the SST ranges between $21.1\text{--}28.3^\circ\text{C}$ (Rasmussen *et al.* 2007), consistent with our results, with the peak of the whale season occurring in temperatures from $26.7\text{--}27.9^\circ\text{C}$. These lower water temperatures appear to coincide with peaks in the primary productivity as indicated by our results, however the peaks in the chlorophyll-a appear at the start of the whale season prior to the whale numbers

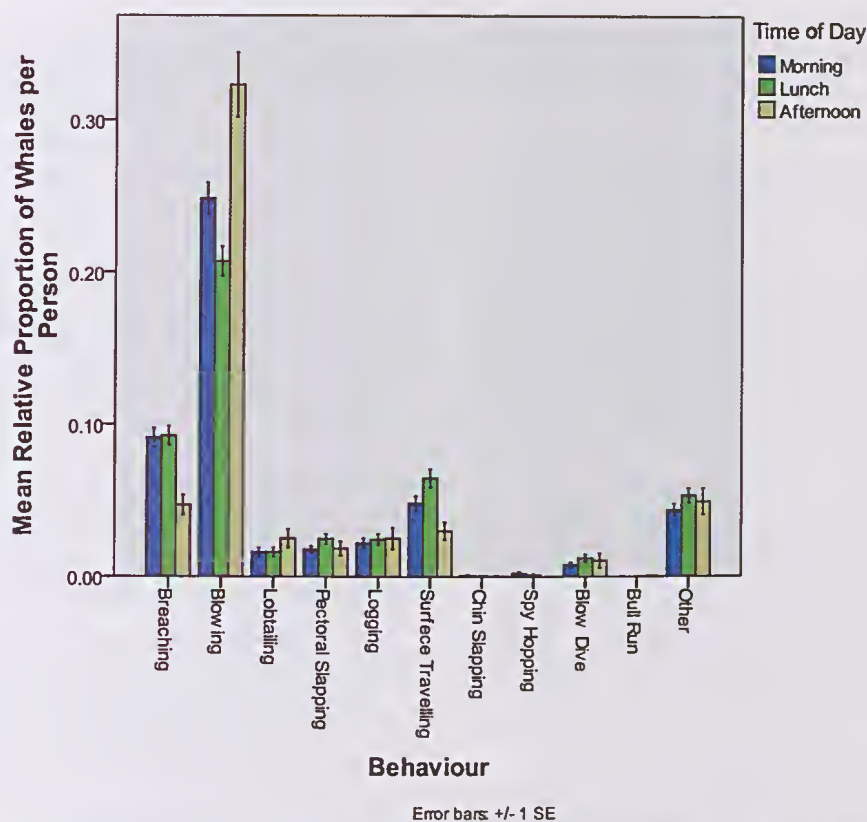


Figure 27. Mean proportion of whales normalised for viewing effort performing different behaviours at each time of day in 2010.

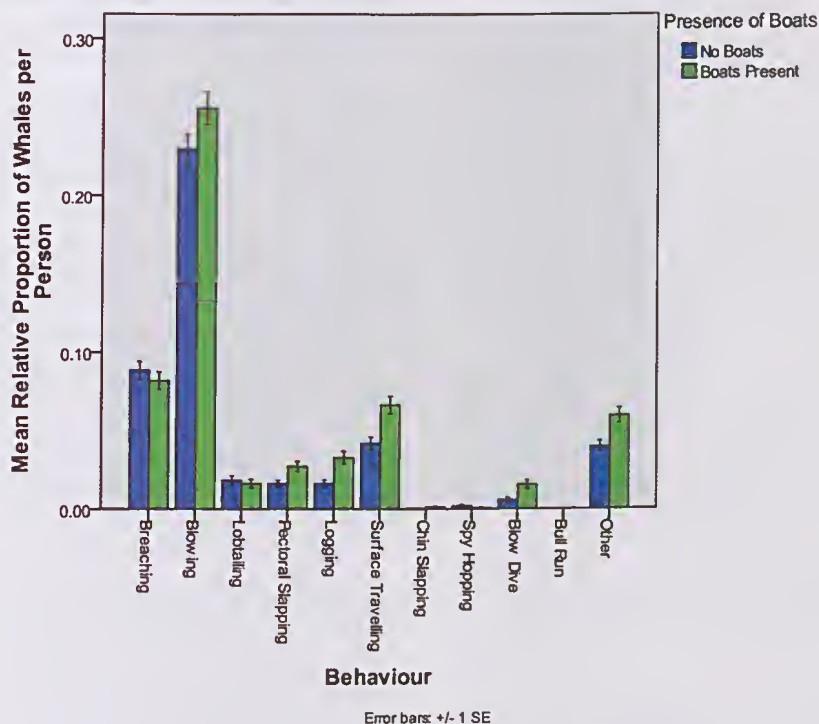


Figure 28. Mean proportion of whales normalised for viewing effort performing different behaviours in the presence and absence of boats in 2010.

reaching their maximum. As chlorophyll-a is used as a proxy of the phytoplankton abundances, and the peak in zooplankton biomass can occur 1–4 months after that of the phytoplankton (Munger *et al.* 2009), this would then put the peak of zooplankton abundance more in line with the peak in the whale season.

As feeding has been observed in other areas of the world during the whale migration and in breeding areas (Canese *et al.* 2006; Stamation *et al.* 2007), we suggest that Pender Bay may also be an important area for opportunistic feeding with feeding having been observed along slicks of breakdown products of *Trichodesmium* sp.

off Cape Leveque. While no whales were observed to be feeding directly in the Bay, we believe that cameras placed in key locations will probably pick these behaviours up in the fullness of time.

The mean percentage of calves peaked later in the season, around September/October, with mothers and calves frequently observed resting close to shore. The occurrence of cows with calves in inshore areas has been well described and it is thought that the calmer conditions inshore aid in conserving the calves' energy which allows for better growth and development of the calf whilst simultaneously providing protection from aggressive adults and Killer Whales (Whitehead & Mann 2000; Ersts & Rosenbaum 2003; Elwen & Best 2004; Double *et al.* 2010).

The relative increase in the percentage of calves is likely the result of two processes. 1. As the adult bulls and cows, both adolescents and mothers without calves begin to leave the Bay, the number of calves present in the remaining population then represents a larger percentage. 2. The mothers and calves travelling south from Camden Sound and the Buccaneer Archipelago stopping off and staging in Pender Bay before migrating south, thereby again increasing the percentage of calves present in the Bay.

These findings further highlight the importance of Pender Bay as a Humpback Whale calving, staging and resting area and are consistent with research conducted by Jenner *et al.* (2001) and McKay & Thiele (2008).

During the course of the study, particularly during 2009, it was observed that the number of whale sightings decreased around midday as well as a shift in the whales' behaviours from more visible displays like blowing to less visible activities such as surface travelling. Research by Karczmarski *et al.* (1998) on the humpback dolphins off Algoa Bay in South Africa also noted a decrease in the dolphins' activities around midday, this was followed by a peak in the activities in the afternoon to levels which were similar to those during morning periods.

Similar trends have also been observed in Beluga whales, where their activity was lower in the morning and midday before increasing in the afternoon (Cornick & Kendall 2008). A study of Humpback whales off Hawaii revealed that the proportion of time spent at the surface was higher in the morning at 0700 hrs and lowest at 0900 hrs before peaking in the afternoon around 1500 hrs (Helweg & Herman 1994), a pattern similar to what we observed. Helweg & Herman (1994) also found that the number of breaches and tail-slaps was greatest at noon, which we also found, and to which they believe serves as visual displays to other whales. While the daily shifts in whale behaviours are still not fully understood, we believe that with continued observation of the whales, the patterns and likely causes of these changes will become more apparent.

Our results indicated that there was little variation in the number of whales sighted with respect to the state of the tides with the exception of the increased number of whales sighted on the incoming tide (Fig. 23). While we are still unsure of the potential effects of the tides on the whales we believe the tidal movements are of more

importance to mothers and calves, which are frequently seen drifting in and out of the Bay, which we believe to be a means of conserving energy by passively drifting with the tides. It was also observed that increased whale sightings occurred during neap tides (Fig. 24), however the reason for the increase during neap tides still remain unclear and as such further study would be needed to elucidate the exact effects of the tides on the whales.

The presence of boats appeared to impact on both the number of whale sightings and their behaviours (Figs. 26 and 28). We don't believe that the whales are attracted to the boats in any way, but rather the boats frequent the bay more in calmer sea conditions coincident with better visibility for viewing the whales and hence the larger number of individuals recorded. We believe we are simply witnessing an indirect correlation as both boats and whale counts are favoured by similar environmental conditions such as calmer weather (Figs. 21 and 25). Survey designs clearly need to take into full consideration visibility-related variables.

Common behaviours observed involving whales and other cetaceans in short term responses to boats, are to increase swimming speed, change direction, and spend more time submerged on dives (Corkeron 1995, Scheidat *et al.* 2004; Stamation *et al.* 2010). These responses were evident during this study as indicated by the increase of surface travelling and blow diving behaviours (Fig. 28). We also observed an increase in the number of whales seen logging when boats were present. This suggests that in addition to the above mentioned responses, the whales may also choose to remain stationary while the boats pass through the area.

Research has shown that the prolonged exposure to short term disturbances by boats can result in population declines of cetaceans, with decreased reproductive success and reduced fitness (Bejder *et al.* 2006(a),(b); Williams *et al.* 2006; Lusseau and Bejder 2007). This could become an issue for Pender Bay in the future, with likely increased access to the adjoining land area and corresponding increases in the number of people wanting to utilise the bay. The appropriate management plan needs to take this into consideration.

We believe the survey technique developed is a pragmatic one with large numbers of volunteers in a highly remote location such as the Kimberley coast. The logistics of implementing a study of this kind relies on access to the permanent marine field location site on the shores of Pender Bay with the Two Moons Whale and Marine Research Base providing basic services. Pender Bay is an ideal location to observe humpback whales in their natural environment, as we believe that ship-based surveys will likely have some effect on humpback whale numbers and behaviours. An unobtrusive cliff top location allows observers to experience humpback whales displaying their natural behaviours including birthing and mating.

Whilst distance estimates of whales offshore remain an ongoing challenge, we believe that as long as the technique is standardised, then it remains a pragmatic way of operating, noting that on very busy observation periods, such as early August 2009 we sighted as many as 91 (unstandardised) whale sightings in a five minute counting period.

In the future, it is important to further elucidate humpback whale distributions within Pender Bay based on habitat types and the morphology of the sea floor and undertake some local primary productivity work based on the fact that we postulate that whales are feeding in this region on an opportunistic basis. In order to make sense of other trends found from this study, we suggest further monitoring of the area as well as collecting additional experimental data that will allow for us to process and analyse more quantitative information using appropriate statistical analyses. Future surveys should ideally attempt to quantify the absolute abundance of Australian west coast humpback whales utilising methods such as those described in Noad *et al.* (in press).

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The Saltwater Crocodile, *Crocodylus porosus* Schneider, 1801, in the Kimberley coastal region

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Abstract

The Australian Saltwater Crocodile, *Crocodylus porosus*, is an iconic species of the Kimberley region of Western Australia. Biogeographically, it is distributed in the Indo-Pacific region and extends to northern Australia, with Australia representing the southernmost range of the species. In Western Australia *C. porosus* now extends to Exmouth Gulf. In the Kimberley region, *C. porosus* is found in most of the major river systems and coastal waterways, with the largest populations in the rivers draining into Cambridge Gulf, and the Prince Regent and Roe River systems. The Kimberly region presents a number of coastlines to the Saltwater Crocodile. In the Cambridge Gulf and King Sound, there are mangrove-fringed or mangrove inhabited tidal flats and tidal creeks, that pass landwards into savannah flats, providing crocodiles with a landscape and seascape for feeding, basking and nesting. The Kimberley Coast is dominantly rocky coasts, rocky ravines/embayments, sediment-filled valleys with mangroves and tidal creeks, that generally do not pass into savannah flats, and areas for nesting are limited. Since the 1970s when the species was protected, the depleted *C. porosus* populations have recovered across northern Australia. Monitoring shows large geographical variations in current population abundance between and within rivers of the Northern Territory, Queensland and Western Australia, and modelling shows strong support for linkage to the ratio of total area of favourable wetland vegetation (*Melaleuca*, grass and sedge) to total catchment area, rainfall seasonality, and other climate parameters.

Keywords: Saltwater Crocodile, *Crocodylus porosus*, Kimberley

Introduction

The Australian Saltwater Crocodile or Estuarine Crocodile, *Crocodylus porosus* Schneider, 1801, is the world's largest living reptile and is an iconic species of the Kimberley region of Western Australia. Considerable research has been conducted into the biology and status of *C. porosus* in northern Australia, particularly in the Northern Territory. The species' biology, population dynamics, recovery since protection and management have been the subject of intensive research efforts over the last 35 years (e.g. Magnusson 1980a, 1980b; Bayliss & Messel 1990; Messel & Vorlicek 1985, 1986; Webb *et al.* 1983, 1984, 1987b, 2000; Webb & Manolis 1989, 1992; Mawson 2004; Fukuda *et al.* 2007, 2010). As part of the joint Royal Society of Western Australia and Western Australian Marine Science Institute Symposium on Kimberley Marine and Coastal Science, we have endeavoured to provide a summary of the information on the species, outlining its history, palaeontology and phylogenetic relationships, biogeography, biology, habitats, nesting requirements, population dynamics, and some behavioural characteristics, with a literature that the reader can access for further information.

History

The rivers of northern Australia have been well known for the presence of crocodiles since the early days of colonisation and exploration, and as Australia's prominent predator in its northern regions, the Saltwater Crocodile has taken the lives of many unsuspecting people, their pets and livestock (Caldicott *et al.* 2005). In the 1950s and 1960s *C. porosus* was hunted for its skin throughout its distribution, and it is estimated that around 270,000 skins were exported between 1945 and 1972 (Webb *et al.* 1984). The days of unregulated hunting slowly ended as hunters themselves recognised that the resource had been over-exploited, and by the late 1960s there were so few *C. porosus* remaining that hunting was uneconomical. The unsustainable harvesting was formally ended by the Western Australian Government in 1969, followed soon after by the Northern Territory in 1971, and Queensland in 1974. Over the following decade *C. porosus* populations began to recover as a result of legislative protection but also because their habitats across northern Australia were largely intact. At the time of protection, populations comprised mainly juveniles, with few adults. By the late 1970s crocodile sightings became more common, and after several well-publicised crocodile attacks fears that a growing crocodile

population would interfere with and inhibit a growing human population led to a more proactive form of crocodile conservation in the Northern Territory (Webb *et al.* 1987a). A major public education program (Butler 1987) and a problem crocodile program were two key elements of a management program designed to enhance public safety. In both the Northern Territory and Western Australia it was recognised that for the public to accept large populations of large Saltwater Crocodiles, they needed to perceive crocodiles as being beneficial to local people. This meant encouraging activities that generated positive linkages with crocodiles, and trying to minimise activities that generated negative linkages. The subsequent management programs have incorporated sustainable use as a means of achieving positive benefits (e.g. CALM 2003; DEC 2009; Leach *et al.* 2009), and a problem crocodile program as a means of eliminating negative linkages. To date, the sustainable use of wild *C. porosus* populations has not been adopted in Queensland (Read *et al.* 2004), although some advances are now being made in that direction.

Palaeontology and phylogenetic relationships

The crocodylians appear as a fossil group in the Triassic as part of the archosaurs, the group that includes the dinosaurs (Nash 1975; Buffetaut 1979; Taplin 1984; Bellairs 1987). With the birds, crocodylians are the only surviving archosaurs. The genus *Crocodylus* first appeared in the Palaeocene some 65 million years ago (Archer 1976; Willis & Molnar 1997; Mackness & Sutton 2000). Modern crocodylians, as large amphibious and carnivorous reptiles, and as water's edge predators, have much in common with each other. They inhabit tropical and subtropical lakes, rivers and coasts, lay their eggs in nests constructed on land, and their morphology and physiology have been shaped by similar lifestyles, allowing many generalisations to be made about the group as a whole. Research work on extant forms has emphasised homogeneity within the group rather than the differences (Cohen & Gans 1970; Densmore & Owen 1989; Densmore & White 1991), with the relative homogeneity appearing to be the remnants of a large radiation which peaked in the Mesozoic – their hard parts are very similar to those of fossil forms of the Triassic (Steel 1973, 1989). The three extant lineages (Crocodyloidea, Alligatoroidea and Gavialoidea) were distinct by the Upper Cretaceous. Phylogenetic relationships of crocodylians suggest the possibility that many or all of the extant crocodylids might be derived relatively recently from marine-adapted ancestors with physiological capabilities similar to *C. porosus* (Taplin *et al.* 1985; Taplin & Grigg 1989; Salisbury & Willis 1996).

In recent years there has been extensive research on the history and systematic relationships of fossil crocodylians discovered in Australia, several from within the range of *C. porosus* and the related Australian Freshwater Crocodile *C. johnstoni* (Willis 1997). The diverse crocodile fauna, which appears to have been dominant for much of the Tertiary, became extinct during the Pliocene in association with the collapse of the Australian megafauna (Willis 1997). *Crocodylus porosus* appears suddenly in the fossil record in early Pliocene

deposits at Bluff Downs, Queensland (Archer 1976). Interestingly, *C. johnstoni* appears in the Pleistocene, suggesting that it may have originated from a *C. porosus* ancestor (Willis & Archer 1990).

Distribution

Biogeographically, *C. porosus* is distributed from the east coast of India across to southeast Asia, including Vietnam, Cambodia, Thailand, the Philippines, Malaysia and Indonesia, and through Papua New Guinea and Australia. Australia represents the southernmost extent of the range of the species. In Western Australia *C. porosus* now extends to Exmouth Gulf (Fig. 1), and lone male crocodiles have also been recorded as resident in isolated rivers and tidal creeks in the Pilbara region. Vagrant crocodiles have been recorded in marine habitats as far south as Carnarvon on the mid-west coast.

In the Kimberley region, *C. porosus* is found in most of the major river systems and coastal waterways, including: the Ord, Patrick, Forrest, Durack, King, Pentecost, Prince Regent, Lawley, Mitchell, Hunter, Roe and Glenelg Rivers and Parrys Creek. The largest populations occur in the rivers draining into Cambridge Gulf, and the Prince Regent and Roe River systems of the east and northwest Kimberley region. Much lower densities occur in the rivers draining into King Sound and Stokes Bay in the west Kimberley.

Coastal habitats in the Kimberley region

The Saltwater Crocodile occurs in a range of habitats, including inland freshwater settings such as lakes, swamps, billabongs and river courses, and coastal and marine habitats. The definition of what is a 'crocodile habitat' will depend on whether the crocodile is viewed as permanently occupying a niche as a resident (in which case it is permanent, and may patrol a specific territory, or inhabit a specific tidal creek), or in fact is a temporary resident, or is a vagrant, occupying an environment on a transitory basis.

The Kimberly region presents a number of coastlines to the Saltwater Crocodile (Fig. 1). In the Cambridge Gulf area, there are mangrove-fringed or mangrove inhabited tidal flats and meandering tidal creeks that pass landwards into savannah supratidal flats and savannah floodplains (Fig. 2). This provides crocodiles with a landscape and a seascape where they can feed, bask and nest. The Kimberley Coast (*sensu* Semeniuk 1993) is a ria shore dominantly with rocky coasts, cliffs, bouldery shores, marine-flooded narrow rocky ravines and embayments with sandy beaches and sandy bars at their seaward openings; in the larger river-developed valleys and gulfs, there are sediment-filled valley tracts with mangrove-fringed or mangrove inhabited tidal flats and meandering tidal creeks, but these generally do not pass landwards into savannah supratidal flats and savannah floodplains. Areas for nesting are somewhat limited.

King Sound is similar to Cambridge Gulf in that there are mangrove-fringed or mangrove inhabited tidal flats and meandering tidal creeks but they pass landwards into extensive salt flats and as such do not provide crocodiles with much opportunity to nest. The western

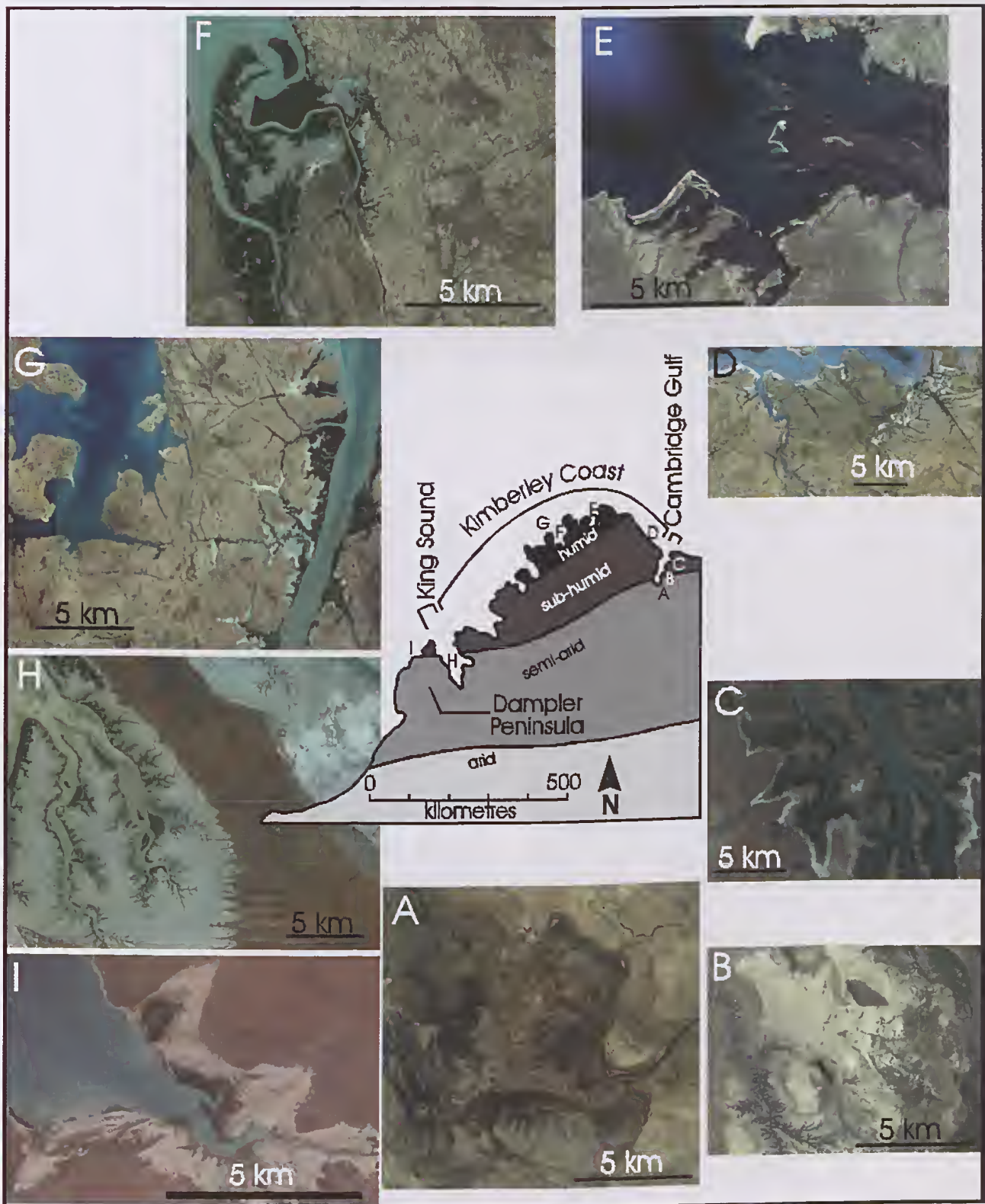


Figure 1. The four coastal types that are habitat to the Saltwater Crocodile, with aerial photographs of the coastal zone typical of each: (1) the Cambridge Gulf area, (2) the Kimberley Coast (*sensu* Semeniuk 1993) with rocky coast, narrow ravines, and deltas, (3) King Sound, and (4) the west coast of Dampier Peninsula. The central map shows the climate setting of the Kimberley region, and the location of aerial photographs: (A) floodplain in southern Cambridge Gulf; (B) mangrove fringed salt flats and tidal creeks of middle Cambridge Gulf; (C) tidal flats, salt flats and tidal creeks more extensively inhabited by mangroves in northern Cambridge Gulf; (D) the dominantly rocky coast and mangrove-filled narrow ravines of the northeastern Kimberley Coast; (E) densely mangrove-inhabited delta of the Drysdale River; (F) densely mangrove-inhabited delta of the Lawley River; (G) rocky shores, narrow mangrove-inhabited ravines west of the Mitchell River, and the narrow (dominantly rocky) gulf of the Mitchell River; (H) mangrove-fringed salt flats and tidal creeks of middle King Sound; and, (I) mangrove-fringed salt flats of the embayment of Beagle Bay.



Figure 2. Images of contrasting habitat; Saltwater Crocodile on a rocky coast at Croc Creek in Yampi Sound opposite Cockatoo Island (photograph courtesy of One Tide Charters, Derby), and on the upper reaches of a floodplain (Ord River) in the Cambridge Gulf area (photograph W.R. Kay).

coast of Dampier Peninsula is comprised of rocky shores and local embayments filled with and with mangrove-fringed or mangrove inhabited tidal flats and meandering tidal creeks; locally the salt flat passes landward into freshwater swamps.

A selection of landscapes and seascapes in the Kimberley region is shown in Figure 2. This shows areas where crocodiles may inhabit and nest, and the areas such as mangrove vegetated tidal flats and tidal creeks, backed by salt flats, where crocodiles may inhabit but with little opportunity for nesting.

Burbidge (1987) also noted that the areas of the Kimberley inhabited by *C. porosus* differ markedly from most of the Northern Territory, describing the Kimberley coastline and hinterland as chiefly composed of steep, rugged, ancient, deeply faulted sandstones with access up many rivers blocked to crocodiles by waterfalls and their associated gorges. There are few areas of floodplain and very few freshwater swamps and hence breeding habitat is relatively scarce.

It would appear, therefore, from the description of coastlines above, that the carrying capacity of the Kimberley river systems and the Kimberley region as a whole is much less than that of the Northern Territory. This notion is supported by an assessment of trade and other statistics from the 1946–74 hunting period (Webb *et al.* 1984).

Biology

Crocodylians are sturdy lizard-shaped reptiles, with a well-armoured head and trunk and with horny skin and scales, reinforced with bony plates. In modern crocodylians, the head is generally flattened and the snout elongated. The skeleton is typical of that of tetrapods in general and of archosaurs in particular, with the skull and pelvis particularly specialised (Romer 1956). The structure of the cervical vertebrae, the osteoderms, and the ribs protect the ventral surface (Steel 1973).

The nasal capsules lie near the tip of the snout, and nostrils which can close in the external nares tend to be raised above the tip of the snout – thus submerged crocodylians are inconspicuous when drifting toward terrestrial prey. During submergence, the palatal flap, a rigid plate of tissue at the rear of the oral cavity, closes the posterior buccal space against the entry of water, and the nostrils can be closed tightly. Skull and jaws are solid and together with the strong peg-like teeth can maintain an effective hold on prey (Iordansky 1973). The vertically undulating jawline coincides with the distribution of the largest teeth, accentuating the pseudo-heterodonty. In the Crocodylidae, upper and lower teeth alternate at occlusion, and the 4th dentary tooth fits into a lateral notch at or near the junction of the pre-maxilla with the maxilla. As a result, the teeth of crocodiles are far more conspicuous than those of alligators when the mouth is closed. Iordansky (1973) and Langstone (1973) provide useful reviews of the structure of both modern and extinct crocodylian skulls.

The skin of crocodiles is covered with keratinised scales, many of which are reinforced with bony plates, or osteoderms (Brazaitis 1987). Saltwater Crocodiles have no osteoderms in the belly scales. All “true” crocodiles, such as *C. porosus*, have Integumentary Sense Organs (ISO) on the scales. The function of ISOs, which are absent in the alligatorids, remains unclear, and it has been suggested that they are osmoreceptors, designed to detect salinity (Jackson *et al.* 1999). The ISOs on the jaws are well vascularised and innervated and considered to be involved in the detection of vibrations in the water – Soares (2002) termed these “Dome Pressure Receptors”. Osteoderms are prevalent in the dorsal and nuchal scales, and commonly bear conspicuous ridges. The scales themselves are covered by hard, wear-resistant beta-keratin, and the skin between the scales is covered with less rigid alpha-keratin.

The skin provides a significant barrier to the movement of both water and ions. The Crocodylidae are good ionic and osmotic regulators, and ionic composition

is similar between species [see Grigg *et al.* (1986), Taplin (1988) and Mazzotti & Dunson (1989)]. Larger individuals, with a lower surface area/mass ratio, can tolerate exposure to osmotic stress longer than smaller ones. Maintenance of internal homeostasis is frequently managed against a threat of flood or drought in fresh and salt water, respectively. Whereas most crocodilians are found in fresh water, *C. porosus* occurs routinely in hyperosmotic estuarine habitats while many others are exposed at least to brackish environments (Taplin 1988). Hatchlings of *C. porosus* are able to survive and grow without access to fresh water (Grigg *et al.* 1980; Taplin 1984). The presence of functional salt glands on the tongue provides *C. porosus* with an effective means of ridding the body of excess salt without the loss of body water at the same time.

Adult *C. porosus* are large, and the species shows a pronounced sexual dimorphism in terms of size. Males grow larger and often more rapidly than females, reaching an average maximum length of around 5 m (Webb and Manolis 1989) – however, some individual males may reach 6–7 m, and weigh over 1000 kg (Whitaker and Whitaker 2008). Females are much smaller, generally not exceeding 3 m in length. In the wild, males are sexually mature around 3.4 m (16 years) and females at 2.3 m (12 years) (Webb and Manolis 1989). At the same size, males and females cannot be identified on the basis of external characteristics.

Saltwater Crocodiles use behavioural means to regulate body temperature within optimal limits, moving between land and water to heat and/or cool themselves. During the cooler times of the year, basking during the day is prolonged in order to raise body temperature, whereas during the warmer times of the year the hotter parts of the day are spent in the water (see Lang 1987b).

Further description and discussion of crocodile morphology, physiology, natural history, biogeography and phylogeny and general biology may be found in Grigg *et al.* (1980), Taplin (1984, 1988), Wright & Moffat (1985), Webb *et al.* (1987), Mazzotti & Dunson (1989), Cogger (1993, 1996), Grigg and Gans (1993), Cooper-Preston & Jenkins (1993), Molnar (1993), Richardson *et al.* (2002), and Webb and Manolis (1989).

Diet and feeding behaviour

The diet of *C. porosus* varies with the size of individuals. Hatchlings feed mainly on small crabs, prawns and insects (Webb *et al.* 1991; Webb & Manolis 1989). With increasing size, crocodiles feed on a greater variety of larger food items, including fish, crabs, turtles, birds and mammals, with prey such as cattle and horses eaten only by the largest of crocodiles (Taylor 1979).

Saltwater Crocodiles typically employ a “sit and wait” strategy for hunting prey at the water’s edge. The minimum exposure posture allows only the eyes, ears and nostrils to be exposed at the water’s surface, and the body to be hidden underwater. Unsuspecting prey are grabbed quickly, and killed with a single snap of the jaws or by being dragged underwater and drowned. The tail can be used to accelerate the body completely out of the water or to launch a rapid lunge at prey. Small crocodiles will sit at the water’s edge snapping at any movement that occurs

near their jaws. Crocodiles may also employ direct hunting methods, such as stalking prey at the water’s edge or in the water, or using the tail to knock prey out of small trees. Large crocodiles will also scavenge carrion, and individuals have been recorded caching dead prey for later retrieval (Doody 2009).

The crocodilian stomach is a simple bag-like structure that allows heavy objects such as stones to be stored (Richardson *et al.* 2002). Stones are likely to assist in breaking down prey (gastroliths), but a hydrostatic function has also been suggested (hydroliths). The stomach is highly acidic (pH 1–2), and even bones are completely digested. Items made of keratin (feathers, hair) or chitin (insect cuticle) are not digested, but mechanically broken down – hairballs are formed in the stomach and later regurgitated. Large crocodiles can go for long periods (up to 12 months) without food.

Nesting

Nesting for Saltwater Crocodiles is a wet season activity, spanning October to April. Females construct a mound of mud and/or vegetation that is typically located close to permanent water (Webb *et al.* 1977). Freshwater swamps and floodplain habitats associated with tidal rivers are the most common nesting habitats (Webb *et al.* 1977; Harvey & Hill 2003). Mangrove swamps are rarely used. The extent and timing of nesting is related to rainfall and water levels in the preceding dry season. Annual nesting effort may vary by more than 50% between years.

Clutch and egg size are largely determined by female size. Mean clutch size is around 50 eggs, with up to 90 eggs having been recorded (see Webb *et al.* 1983). On average, some 75–80% of wild *C. porosus* eggs would not be expected to hatch. Although a mound-nesting strategy is designed to maintain the eggs above the water, flooding is the main cause of embryonic mortality for *C. porosus* (Magnusson 1982; Webb *et al.* 1983). In some cases, overheating caused by the decomposition of certain types of vegetation (e.g. *Phragmites*) used in the construction of the nest may contribute to mortality (Webb and Cooper-Preston 1989). Examination of *C. porosus* nests in the Kimberly area indicated that overheating due to high ambient temperatures was a potential cause of mortality in some areas (G Webb Pty Ltd 1989).

Incubation period is dependent on temperature (e.g. 80 days at 32°C, 90 days at 30°C). Like other crocodilians, Saltwater Crocodiles have temperature-dependent sex determination: 100% males are produced at 32°C, 100% females at < 31°C, and 100% females at > 33°C (Webb *et al.* 1987c). When the eggs are ready to hatch the hatchlings make chirping sounds (Britton 2001), and the female helps them by digging them out of the nest, and taking them to the water’s edge in her mouth – she will guard them until they are independent. Extensive studies of nesting, egg characteristics, survivorship, and hatchling dispersal of *C. porosus* has been undertaken by Magnusson (1979a, 1979b, 1979c, 1980a, 1980b, 1982), Webb *et al.* (1983) and Webb & Messel (1978).

Nesting habitat for *C. porosus* is limited in the Kimberley region, and only the Ord, King and Roe River

systems support suitable vegetation for significant nesting. A few nests have been recorded in other river systems such as the Drysdale and Prince Regent Rivers and Admiralty Gulf Creek. Saltwater Crocodiles occur in four of the 10 conservation reserves > 2000 ha in area in the Kimberley region that have rivers running through them.

Population dynamics

Mortality rates from egg to maturity are high. Based on available information Webb & Manolis (1993) predicted mean estimates for survival rates for several size classes of wild *C. porosus*: eggs 30% hatch; hatchlings (0–1 year) 12%; 1–2 years 85%; 2–3 years 85%; 3–4 years 85%; and, 4–5 years 85%. Survival rates of older individuals are difficult to estimate, but < 1% of eggs are expected to reach maturity. *Crocodylus porosus* may live for more than 50 years.

As *C. porosus* populations in northern Australia began to recover, it became clear that density-dependent factors were important to the rapid increase in abundance seen in the first few years of protection, and subsequent changes in size structure thereafter. In rivers studied in detail, numbers of small crocodiles over time were negatively correlated with numbers of larger crocodiles. With increasing numbers of large crocodiles, the numbers of small crocodiles decreased, either through exclusion from the river, or through being killed by other crocodiles (Webb & Manolis 1992). Survival rate for hatchlings was unrelated to numbers of larger crocodiles, but was dependent on the number of hatchlings present – the higher the number of hatchlings that were recruited into a river the lower the survival rate to 1-year-of-age. This density-dependent survival rate is thought to compensate for the annual egg-harvest in the Northern Territory, which has been sustained, without restocking, for over 25 years.

Behaviour

Like other crocodilians, Saltwater Crocodiles have a rich repertoire of behaviours through which they communicate, including vocal (audible and sub-audible), visual and chemical signals (Lang 1987a). Relative to American Alligators *Alligator mississippiensis*, Saltwater Crocodiles are not as “vocal”, although vocalizations are clearly an important means of communication between individuals. For example, hatchlings utilise a high-pitched “bark” in response to danger, to which adults and larger juveniles will respond. Such vocalizations may also serve to maintain hatchlings within a creche in the first few months of life.

Female Saltwater Crocodiles exhibit a high degree of maternal care for their eggs and young. They will aggressively defend their eggs/nests against predators (including humans), assist hatchlings to emerge from the nest, and even carry them to the water.

Relative to other crocodilian species, Saltwater Crocodiles are highly territorial and adults are generally intolerant of conspecifics. Injuries caused by intra-specific fighting are commonplace, particularly in larger individuals (Webb & Messel 1977). Younger subordinate

crocodiles may be forced out of areas by larger crocodiles, and forced to seek unoccupied territories elsewhere. This may result in movement out of rivers and subsequent movement around the coast until suitable areas are located. For example, since the late 1970s the Northern Territory’s Problem Crocodile Program has captured and removed any crocodiles moving into Darwin Harbour from around the coast (Nichols and Letnic 2008). However, some individuals may move upstream, into freshwater areas typically outside the range of the species, and sometimes into recreational areas used by people – this is a management issue being addressed in the Northern Territory (Letnic and Connors 2006).

In the Ord River the numbers of *C. porosus* in upstream, non-tidal sections of the river have increased significantly in recent years, and some individual *C. porosus* have been recorded from Lake Kununurra and Lake Argyle (DEC, unpublished data). Other movements relate to the reproductive season (e.g. females moving to nesting areas, males seeking females; Kay 2004), and satellite telemetry is now revealing as yet “inexplicable” movements by adult *C. porosus* in and out of core areas of activity (WML, unpublished data).

Saltwater Crocodiles are excellent swimmers, with a relatively higher proportion of their body length represented by the tail, and greatly reduced bony dorsal armour – both characteristics are considered adaptations for swimming long distances. Individual Saltwater Crocodiles are commonly sighted well out to sea, and the record distance is around 2000 km (Manolis 2005). Crocodiles can also travel substantial distances overland (Walsh & Whitehead 1993; Webb and Manolis 1989).

Current management practices, conservation status, and monitoring

The management of crocodiles in northern Australia has been discussed by Webb *et al.* 1987a) in relation to habitat, population dynamics, nesting, harvesting and farming, and in Western Australia by Burbidge (1987) and Mawson (2004). The depleted *C. porosus* populations have recovered strongly across northern Australia in the 40 years since the species was protected (e.g. Fukuda *et al.* 2010). The recovery of the *C. porosus* population in the tidal section of the Ord River is shown in Figure 3.

Population monitoring shows large geographical variations in current abundance between and within rivers of the Northern Territory, Queensland and Western Australia. The historical abundance of *C. porosus* also varied between rivers (see Webb *et al.* 1984), and there is no reason to suspect that this will not continue to be the case in the future. The higher abundance of *C. porosus* in the Northern Territory is related to the greater extent of habitat and nesting there.

Broad-scale environmental influences on population abundance have been examined by modelling the species-environment relationships across northern Australia. The models show strong support for the linkage to the ratio of total area of favourable wetland vegetation types (*Melaleuca*, grass and sedge) to total catchment area, a measure of rainfall seasonality, namely the ratio of total precipitation in the coldest quarter to total precipitation in the warmest quarter of a year, and

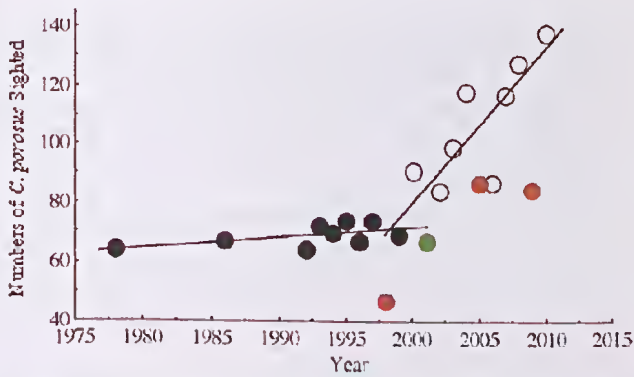


Figure 3. Recovery of the Saltwater Crocodile populations in the tidal Ord River, Western Australia (DEC, unpublished data). Helicopter count index for *C. porosus* in the Ord River monitoring zone, 1978–2010. Line for 1978–1999 indicates the non-significant linear regression ($r^2=0.36$, $p=0.09$; 1998 excluded due to particularly warm conditions), and the line for 2000–2010 indicates the significant linear regression ($r^2=0.55$, $p=0.02$; 2001, 2005 and 2009 excluded due to high or low temperatures during surveys).

the mean temperature in the coldest quarter of a year (Fukuda *et al.* 2007). There was not any clear negative association with landscape modification, as indicated by the extent of high-impact land uses or human population density in catchments. Thus geographical variations in crocodile density are mostly due to differences in habitat quality rather than the management regimes adopted in the respective jurisdictions.

In Western Australia, crocodiles usually cannot be commercially harvested in conservation reserves. The conservation estate within the Kimberley region (where most of the crocodiles live) amounts to an area in excess of 2.88 million ha (DEC 2009). Lands supporting other crocodile populations are vested in Crown Reserves and Aboriginal Lands. The proportion of land that actually constitutes riparian habitat suitable for crocodiles is a much smaller subset of these areas. The circumstances whereby crocodiles may be harvested from a conservation reserve includes where such actions are deemed a necessary operation under the *Conservation and Land Management Act 1984* or where an area management plan specifies that the management of overabundant populations was warranted or to protect human life from large crocodiles assessed as posing a direct threat to safety and welfare.

The conservation of crocodiles in Western Australia is potentially threatened by a range of environmental and anthropogenic factors. Many of these, such as drought and flood and disease, are ecosystem and environmental processes that exist in the realm of the larger environment. However, these processes are not considered a long-term threat to the conservation of crocodiles (DEC 2009). Potential anthropogenic threats to the conservation of crocodiles principally arise from the commercial harvest and habitat destruction (through pastoralism, mining and damming of waterways or use of surface water for mining or agriculture purposes). However, in 20 years of commercial harvesting in Western Australia, viable *C. porosus* populations have been maintained across their natural range and, moreover, the distributional range of the species appears

to have expanded, with increasing numbers of sub-adult and adult male crocodiles being recorded at Broome, and vagrant animals also being recorded further south along the Pilbara coast, and as far south as Carnarvon (DEC 2009).

However, to ensure that the commercial crocodile harvest in Western Australia remains sustainable and does not jeopardise the viability of crocodile populations across their range, the Department of Environment and Conservation enacts a range of management controls, including regular and ongoing monitoring of crocodile populations, setting commercial harvest quotas at levels considered to be ecologically sustainable for the populations, management of problem crocodiles, providing refuge habitat, and assessing the impacts of commercial crocodile harvest on other species, habitats and ecosystems (DEC 2009).

The conservation status of the commercially harvested crocodiles in Western Australia largely reflects their former abundance and historical utilisation. Commercially harvested crocodiles in Western Australia are currently listed as 'Other Specially Protected Fauna' under the provisions of the *Wildlife Conservation Act*, but are not listed under the Australian Government *Environmental Protection and Biodiversity Conservation Act*. The International Union for the Conservation of Nature's Red List of Threatened Species identifies *C. porosus* as Lower Risk-Least Concern (Jenkins 1987; Webb *et al.* 2010). The Australian population of *C. porosus* is listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), thus allowing regulated trade in the species from Australia. At a State level, Western Australia's approved management program (DEC 2009) provides compliance with Australia's obligations to CITES.

Crocodiles and Traditional Owners

Traditional Owners in the Kimberley and northern Australian region have had a long history with the Saltwater Crocodile. The crocodile has figured in their rock art, legends, and stories, and they have hunted them for food. Conversely, the crocodile has preyed on the indigenous people. As such, the crocodile has insinuated itself into Aboriginal culture, and is of particular significance where it is the totem for particular clans (e.g. Lanhupuy 1987). In the Northern Territory, landowners benefit economically from Saltwater Crocodiles through the ranching program (Leach *et al.* 2009; Webb *et al.* 1996).

Crocodile attacks in Western Australia and lessons for the future

Records from published newspaper accounts along with government records indicate that since 1947 there have been 11 attacks on humans attributed to *C. porosus* in Western Australia. Of these attacks, three were fatal – one occurred in 1947, and involved a British seaman in Wyndham Harbour, where there was clear evidence that a crocodile had fed on the man, but not conclusive proof that the crocodile had killed him. The other fatal attacks in Western Australia occurred in 1980 (Wyndham) and 1987 (Prince Regent River). Non-fatal attacks have been

reported from both riverine and marine habitats (WMI, unpublished data).

With increasing development along the Kimberley and northern Pilbara coastline there is an increased likelihood of adverse interactions between people during works programs or recreational activities. Added to this is the fact that many of the people who will be moving to those areas will be 'crocodile naïve', this indicates that specific public education programs will be necessary to raise worker awareness of the risks of living in areas occupied by crocodiles.

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The Kimberley Coast – Saltwater Country – monitoring and management of the coastal and marine zone

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This contribution is an account of how the Traditional Owners of the Kimberley coastal region are involved in land management through biological surveys, data collection, monitoring, and on-ground land management practices.

The rocky coast of the Kimberley, known as Saltwater Country by the Traditional Owners of the region, representing the peoples of Bardi Jawi, Malaya, Dambimangarri, Uuguu and Balanggarra, is the area in discussion. The Traditional Owners of this region have a long history of association with the landscape, seascape, flora and fauna and, as such carry a long term core knowledge on its environment and biology. Their involvement with the coast, islands, and marine environment dates far back as the early part of the Holocene (7000 years), when the Kimberley region was flooded by rising sea levels after the last Ice Age. They have therefore a long term traditional familiarity with the landscape, seasonal processes, and biological patterns. Since they see the land, coast and seascape as part of their traditional lives and that they are custodians or caretakers of this environment, their long-term familiarity and information base serves them well to be managers of the coast and seascape, and to be involved in monitoring.

There is need for monitoring and management of the Kimberley Coast and seascape, because in recent times there has been increased tourism, overfishing, exploitation of natural resources, increase in fires and burning out of coastal vine thickets and rainforest, and there have been pressures on endangered species. In short, the land and coastal lands are being environmentally impacted. This leads on to the conclusion that there is a need for environmental management, but good management beings with it a need for knowledge of what is occurring, such as whether biological stocks are depleting and the extent that tourism and other coastal activities are having an effect on the environments. Effectively, this requires monitoring of the various facets of the environment.

Traditional Owners bring traditional knowledge to monitoring. Because they live or have lived on the coastal lands and islands, and have harvested shell fish, oysters, and shipworm, have hunted turtles and dugongs, and have caught fish and stingrays, they have an on-ground local knowledge of the dynamics of these creatures. They carry traditional knowledge and familiarity about the land, coast and seascape, passed down through the generations that assists in their being able to manage the land and monitor its components. For instance, their knowledge of the migration and arrival and breeding

season of turtles and dugongs is the culmination of long-term observations of patterns, and enables them to be at the right place and right time to hunt or harvest specific species. And thus they can be at the right time and right place for undertaking monitoring.

The Kimberley regional ranger programme facilitated by the Kimberley Land Council on behalf of Traditional Owners, have been involved in documenting, monitoring, and management of the Kimberley Coast and its seascape in a number of ways. They have operated in collaboration with scientists of the World Wildlife Fund (WWF) and officers of Environs Kimberley. The text below and Figure 1 outline some of the activities that the ranger groups have been involved with.

With documenting, they have carried out marine biological surveys, and recording of plants and fauna in the region. Because they know the country and seascape across a number of Traditional Owner groups, some of the recent surveys were to assist in a partnership between Bardi Jawi, Mayala Dambimangarri, Uuguu and Balanggarra. This they achieved, for instance, in a marine assessments for the WWF of whales and Snub-nosed dolphins. The Bardi Jawi rangers lead this survey utilising "cybertracker" technology, integrating western science with traditional knowledge to accurately record data and achieve environmental outcomes. Biological surveys also have involved collecting and recording flora – for instance, the recording flora and vegetation in 50 m square quadrats in vine thickets, and in conjunction with Environs Kimberley, the trapping of fauna to provide an inventory of the biodiversity in vine thickets. They have also been involved with "photo-trapping" with the WWF along vine thickets to document the fauna visiting or living there. Island surveys have been undertaken for biological purposes, and to check for feral rats.

In relation to monitoring they have been involved with recording the arrival, numbers, and nesting of turtles, with the tagging and study of dugongs, with the counting of sea birds, with noting and recording the arrival of exotic diseases and the recording the of the arrival of alien plants, and the recording of the occurrence and effects of bush fires on coastal vine thickets. With the monitoring of turtles and dugongs, the rangers collect data through interviews on who has been hunting for turtles and dugongs, where they have been, how long they have stayed at a place, what they have caught, and what they have observed. Turtle and dugong tagging and the use of satellite tracking also have been used to determine migration of turtles and dugongs in terms of where they have been, and where they are feeding. All these data forms the basis for an information base to help manage the turtles and dugongs and other

sea life. To assist with the management of fish and fish stocks, there are plans to develop a monitoring programme for fishing activities.

Monitoring for the Traditional Owners is part of the "caring for country" that is part of their core philosophy.

In management, the Traditional Owners, as rangers, collate data to understand and design management programmes for various components of the environment. For instance, there are management plans for fires in the coastal vine thickets and for fires in the coastal vegetation in general. There are activities to repair eroding beaches, and to revegetate damaged dunes with native plants. They are involved in rubbish pick-up, beach debris clean-up, and weed removal along the coastal zone. They assist the Australian Quarantine and Inspection Service (AQIS)

and Environs Kimberley in monitoring and reporting of any foreign pests such as fire ants, weeds, and mosquitoes.

In addition to their traditional knowledge, obtained from Elders and their own experience on the coast, rangers obtain further formal qualifications in land management from Kimberley TAFE.

The photographs in this paper (Figure 1) illustrate some of the activities in data collection and monitoring as part of coastal land management and marine management undertaken by the Traditional Owners in the region. The data collected by rangers assist with development of cultural and environmental management plans and the management of resources within Traditional country.



Figure 1. A. Tagging of Dugongs at Pender Bay. B. Ranger in action recording turtle nesting activities. C. Rangers stabilising sand dunes. D. Rangers conducting bird surveys. E. Rangers working with AQIS on Bedford Island in the Buccaneer Archipelago, burning all contents of tourist camp. F. Fire management to create a buffer around the Monsoon Vine Thicket.

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